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Systems Reliability and Performance Pilot-Scale Incineration of Chlorinated Benzenes at the Combustion Research Facility

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SYSTEMS RELIABILITY AND PERFORMANCE

Pilot-Scale Incineration of Chlorinated Benzenes at the Combustion Research Facility

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16. ABSTRACT

A series of 34 test burns was conducted between August 1983 and January 1984 in the pilot-scale rotary kiln incineration system at the USEPA Combustion Research Facility (CRF), using chlorinated benzenes as surrogate Principal Organic Hazardous Components (POHCs), over a range of feed compositions, POHC feed rates, rotary kiln temperatures, and afterburner temperatures. The CRF rotary kiln system consistently produced Destruction and Removal Efficiency (DRE) values above 99.99% for the chlorinated benzenes POHCs. DRE values below 99.99% were obtained during several types of failure mode simulations (flame-out in kiln or afterburner). A large number of Products of Incomplete Combustion (PICs) were produced and identified, a number of which are toxic or possibly carcinogenic. Deliberate reduction of excess air levels resulted in significant production of soot and PICs but did not produce higher levels of CO in the combustion gases. Hot-zone sampling just downstream of each of the two combustion chambers provided for the detailed study of PIC formation and will facilitate the future development of models of the incineration process. Helium injection techniques were used to determine combustion gas flow rates and to measure residence time distributions (which directly affect destruction efficiencies). This report was submitted in fulfillment of Contract 68-03-3128 by Versar, Inc. under the Sponsorship of the U.S. Environmental Protection Agency.

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PREFACE

The USEPA Combustion Research Facility (CRF) is designed to allow detailed engineering and chemical studies of the incineration of hazardous wastes in highly instrumented and closely controlled pilot-scale incineration systems. Experimentation to date has been in a rotary kiln/afterburner system with venturi and packed-tower wet scrubbers. A liquid injection system and a stack gas carbon adsorption unit are currently being installed and should be operational at the CRF by October, 1984.

The purpose of this report is to describe the results of process characterization studies and to report the results of a series of 34 test burns in the rotary kiln system conducted between August 1983 and January 1984. These tests employed chlorinated benzenes (hexachlorobenzene and 1,2,4-trichlorobenzene) as surrogate Principal Organic Hazardous Components (POHCs).

ABSTRACT

A series of 34 test burns was conducted between August 1983 and January 1984 in the pilot-scale rotary kiln incineration system at the USEPA Combustion Research Facility (CRF). These test burns used chlorinated benzenes as surrogate Principal Organic Hazardous Components (POHCs) over a range of feed compositions, POHC feed rates, rotary kiln temperatures and afterburner temperatures.

The CRF rotary kiln system consistently produced Destruction and Removal Efficiency (DRE) values above 99.99% for the chlorinated benzene POHCs. DRE values below 99.99% were obtained during several types of failure mode simulations (flame-out in kiln or afterburner). A large number of products of incomplete combustion were produced during the chlorinated benzene tests. These intermediate products were identified, and a number of them are toxic or possibly carcinogenic. Deliberate reduction of excess air levels resulted in significant production of soot and intermediate combustion products but did not produce higher levels of CO in the combustion gases.

Hot-zone sampling downstream of the kiln and afterburner provided for the detailed study of intermediate product formation and will assist in future modeling of the incineration process. Helium injection techniques were used to determine combustion gas flow rates and to measure residence time distributions (which directly affect destruction efficiencies).

This report was submitted in fulfillment of Contract 68-03-3128 by Versar Inc. under the sponsorship of the U.S. Environmental Protection Agency.

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ABBREVIATIONS

CRF - Combustion Research Facility
POHC - Principal Organic Hazardous Component
PIC - Product of Incomplete Combustion
DRE - Destruction and Removal Efficiency
DE - Destruction Efficiency
HCB - Hexachlorobenzene
TCB - 1,2,4-Trichlorobenzene
TDU-GC - Thermal Decomposition Unit-Gas Chromatograph
VOST - Volatile Organic Sampling Train
MM5 - Modified Method 5 Sampling Train
APC - Air Pollution Control

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The work described in this report was the result of the dedicated effort of the entire Versar Inc. Southern Operations staff, in residence at the USEPA Combustion Research Facility at Jefferson, Arkansas. Considerable support was provided by personnel at the Versar Inc. Springfield, Virginia offices and laboratories.

The continued support of the EPA Project Officer, Mr. Richard A. Carnes, throughout the period of Contract 68-03-3128, has made possible the present fully-operational status of this facility and the production of the extensive test results described in this report. His commitment to the now-realized goal of pilot-scale hazardous waste incineration research is gratefully acknowledged. The advice and counsel of Mr. Tim Oppelt, Chief, Incineration Research Branch, and others at IERL/Cincinnati were invaluable in the performance of this work and in the production of this report.

EXECUTIVE SUMMARY

INTRODUCTION

The USEPA Combustion Research Facility (CRF) has as its overall mission the detailed physical and chemical study of the incineration of hazardous wastes in highly instrumented and closely controlled pilot scale incinerator systems. At present, the technology being utilized is a rotary kiln/afterburner system of nominal 200 lb/hr kiln feed capacity. A liquid injection system and a stack gas carbon adsorption unit are currently under construction and should be operational at the CRF by October, 1984.

The CRF, located on the campus of the National Center for Toxicological Research, Jefferson, Arkansas, houses an incinerator room and associated control room plus locker and shop areas and laboratory space for waste characterization and trace analysis of residual organic compounds in effluent streams. Analytical capability for organics at present includes two gas chromatographs (GCs) with Autosamplers, a high pressure liquid chromatograph (HPLC), and associated sample prep equipment. Hot-zone sampling is available in both the kiln and the afterburner transfer ducts to complement sampling of stack gases. Real-time monitoring of O_2, CO and CO_2 levels is provided by an automated system. EPA Method 5, Modified Method 5 (using cooled XAD-2 resin collection medium), and the volatile organic sampling train (VOST) system for relatively low-boiling organics are routinely used.

At present, the CRF staff consists of eight technical professionals, three technicians, two office staff, and a part-time maintenance person.

During the two years of activity on the CRF Program, the facility has been completed and equipped; master plans for Project QA/QC, Health and Safety, and facility operation and maintenance have been developed and implemented, as has also a Master Research Plan for Fiscal Year 1984; extensive modifications have been made to the rotary kiln system; and test burn series with simulated hazardous wastes have been completed. The RCRA Part B permit for the CRF was recently issued by the State of Arkansas. This will allow experimentation with listed hazardous wastes.

One purpose of this report is describe the results of process characterization studies on the rotary kiln incinerator system. Another purpose is to describe and report the results of the test burn series using hexachlorobenzene (HCB) and 1,2,4-trichlorobenzene (1,2,4-TCB) as surrogate Principal Organic Hazardous Components (POHCs) in a toluene carrier. A total of 34 test burns of typically 8-10 hours duration were performed beginning with final engineering checkout runs on 28 August, 1983, and ending on 26 January, 1984. In addition to test burns over a range of feed compositions, POHC feed rates, rotary kiln temperatures, and afterburner temperatures, tests were run in which various hot-zone sampling methods were evaluated, failure modes were simulated, and test methods for residence time distribution were performed.

Section 1 of the report summarizes program activities to date and provides a detailed description of the CRF and the rotary kiln system. Engineering data from the test series are presented and discussed in Section 2. Section 3 describes the sampling and analysis methods used and presents the analytical results from the tests, including Destruction and Removal Efficiency (DRE) values and identification of intermediate combustion products. Sections 4, 5 and 6, respectively, describe failure mode simulation tests, the methodology and applications of helium dilution for measurement of gas flow rates and residence times, and supporting work in hot zone sampling and scrubber system characteristics. The QA/QC activities at the CRF, including QC work specific to the test burn series, are described in Section 7.

SIGNIFICANT TECHNICAL RESULTS

General

The information contained in this report shows that the CRF rotary kiln system, sampling and analytical support functions, and the supporting

Health/Safety and QA/QC activities are fully operational and capable of routine operation with many types of hazardous wastes. Hot-zone sampling in the kiln and afterburner transfer ducts provides means for detailed study of intermediate combustion products and allows the independent treatment of the two hot zones which is necessary to development of useful system-based models for incineration processes.

Helium injection has proved to be a very good technique for determining combustion gas flow rates, residence times, and residence time distributions (RTD) in the system. RTD has been shown analytically to directly affect destruction efficiency (DE) and thus provides a correlating variable for differences (between DE values at comparable temperatures and residence times) observed with full-scale systems as compared to bench-scale experiments for a given POHC.

The CRF rotary kiln system also appears to be an adequate test bed for evaluation of sampling and monitoring techniques for hazardous waste incinerators.

Results from Engineering Analyses

Incinerator operating characteristics of the rotary kiln system are derived from 26 measurements which document fluid flow, stoichiometry, material and heat balances, and thermal gradients within the system. Some of the pertinent results from analysis and interpretation of these data are summarized below:

- Data from 20 runs for 14 continuous measurements provide a measure of how closely steady-state test conditions were maintained during the test burns. For all except the kiln pressure (a small negative value), the relative standard deviation for each was no greater than 7.5 per cent, showing that the system test conditions were reasonably close to steady-state.

- Three independent determinations of combustion gas flow rate showed consistent but as yet unexplained differences of up to 19 per cent among calculated stack gas flows. The analysis indicates a possible error of this magnitude in the stack gas sampling/analytical results (which, however, did not affect any of the conclusions based on those results).

- The equilibrium between chlorine species (HCl, Cl_2 and Cl•) at elevated temperatures was determined from thermodynamic data. For all test runs, HCl accounts for more than 99.8 per cent of the chlorine present in the kiln and over 98.8 per cent in the afterburner. Most of the rest is present as the free radical Cl•.
- Reynolds numbers in the kiln range from 2300 to 6700, which is in the transition zone between laminar and turbulent flow regimes. Other ranges are:

  Kiln transfer duct - N_{RE} = 5100-14800
  Afterburner - N_{RE} = 7800-13100
  Afterburner transfer duct - N_{RE} = 16800-27000

- Heat losses and heat fluxes were calculated for major portions of the system. For example, it appears that about half of the heat input to the kiln is lost to the surroundings. For the entire system from kiln to a point between the afterburner and scrubber, average heat losses were about 37 per cent of the total system heat inputs.

Results from Chlorinated Benzenes Test Burn Series

Hexachlorobenzene (HCB) and 1,2,4-trichlorobenzene (1,2,4-TCB) were selected as surrogate POHCs because they are recognized as more thermally stable compounds, because they are widely found in certain categories of industrial hazardous wastes, and because they are believed to be precursors to the formation at elevated temperatures of potentially significant products of incomplete combustion. Findings and conclusions believed to be of primary importance to hazardous waste incineration technology are summarized below:

- The CRF rotary kiln system can consistently produce DRE values above 99.99% for refractory POHCs such as the chlorinated benzenes. DRE values below 99.99% were obtained during several types of failure mode simulations (flame-out in kiln or afterburner).

- The feed of HCB or 1,2,4-TCB in toluene produced a large number of products of incomplete combustion which were tentatively identified by GC methods and confirmed by GC/MS. A number of these compounds are toxic or possibly carcinogenic.
- After a test burn with either HCB or 1,2,4-TCB in the feed, significant amounts of the POHC were found to be emitted during subsequent tests wherein the only feed to the kiln was propane fuel. The source of this holdup (or residue) effect during intermittent system operation is as yet undetermined, as is its significance to steady-state commercial incineration operations.
- Analytical data from hot zone samples show that the concentrations of organic compounds found did not correlate with particulate levels, which supports the assertion that the organic molecules are in the vapor state (not strongly associated with particulates) in the hot zones.
- Deliberate reduction of excess air levels resulted in significant production of soot and PICs but did not produce higher levels of CO in the combustion gases.
- Complex chemical interactions occur in the afterburner. In the case of HCB as the POHC, for example, previously formed intermediate combustion products may react to form additional HCB in the afterburner. Under some conditions, POHC output from the afterburner was greater than the POHC input to the afterburner. This could result from reactions between intermediate products, holdup from previous burns, or a combination of these effects.

Planned or Projected Improvements

The planned installation at the CRF of a liquid injection system and a carbon adsorption unit for stack gas treatment have been mentioned previously. The need for other planned or projected improvements has been demonstrated by the work to date on the CRF Program:

- Provision of feed capability for highly-loaded slurries, bulk solids and containerized wastes
- Upgrade of automated stack gas analysis system including NO/NO_x monitoring capability
- Further progess toward automation of data recording and manipulation.

SECTION 1

INTRODUCTION AND PROGRAM OVERVIEW

PROGRAM OBJECTIVES

The incineration regulations for the disposal of polychlorinated biphenyls (PCBs) carefully stipulated the minimum conditions of temperature and residence time that are required for acceptable disposal of this class of compounds. Under the Resource Conservation and Recovery Act (RCRA) regulations for the disposal of all other hazardous material by incineration were promulgated. These regulations stipulate only the requirement that the destruction and removal efficiency (DRE) for the selected Principal Organic Hazardous Constituent (POHC) be in excess of 99.99%. The permit writer is required to establish the minimum operating conditions for a specific incinerator with which the operator must comply. Clearly this approach to regulation demands that there be a strong data base on which the permit writer can draw.

In recognition of the need for a data base on the thermal stability of many chemical compounds as well as on the operating characteristics of various classes of incinerators, the U.S. Environmental Protection Agency embarked on a program to establish the necessary information. A number of incineration test burns have been conducted on commercial-scale facilities using various types of wastes as feed stocks to provide this information.

In addition to the full-scale experiments, the Agency undertook an extended program of study at the University of Dayton on laboratory-scale incineration simulators. A recent version of this technology is the Thermal Decomposition Unit-Gas Chromatograph (TDU-GC) in which small amounts (μg quantities) of test compounds suffice to allow a detailed study, in a non-flame mode, of the thermal kinetics under carefully controlled conditions of exposure temperature, exposure time and atmospheric composition. One result of these studies has been a detailed estimate of the $T_{99.99/2}$ (temperature at which 99.99% of the feed is removed when the exposure time is 2 sec) for a number of compounds. When the results derived from the Dayton effort are compared to those from the large-scale experiments, it becomes apparent that extrapolation over so wide a range will not produce the desired agreement.

The factors that are responsible for the observed lack of correspondence between the laboratory- and commercial-scale results are not well established. On the other hand cost factors strongly suggest the need to find methods of extrapolation from small scale operations (such as those in the laboratory) to large scale technology. The scale-up process would be facilitated by use of a pilot scale incinerator whose size lies between that of the laboratory scale and the industrial scale incinerator, and wherein the gradients of temperature and POHC concentration as well as other factors approximate those of full scale technology. In recognition of this requirement the Agency authorized the design and construction of the U.S. EPA Combustion Research Facility (CRF) and subsequently contracted with Versar Inc. for the operation and maintenance of the CRF under Contract No. 68-03-3128. In addition, experimental facilities have been developed at the EPA Center Hill Facility in Cincinnati, to study flame decomposition kinetics and phenomena to support pilot-scale assessments at the CRF.

The overall mission of the CRF Program is the detailed physical and chemical study of the incineration of hazardous industrial wastes on a highly instrumented and controlled pilot scale incinerator.

Specific program objectives are:

(1) To develop methods of improving the reliability and controllability of the incineration process. By systematically altering the operating parameters of each unit operation, non-compliance of individual CRF subsystems can be purposely induced to define the allowable operating range for that unit, to determine conditions under which products of incomplete combustion (PICs) and hazardous process residues (ash and scrubber liquor) are produced, and to

determine the necessary on-line corrective measures required to restore compliance.

By evaluating surrogates or other indicators for incinerator non-performance, real-time process monitoring and control methods may be developed for use in increasing incineration process reliability and for potentially simplifying permit and compliance evaluations.

(2) To develop incinerator system performance data for regulated hazardous wastes to support current RCRA incinerator regulations and performance standards, and to provide additional technical basis for those future standards which may be necessary.

(3) To develop a technically defensible data base leading to additional understanding of the hazardous waste incineration process and to assist in the development of methods to predict the performance of incinerators as a function of key process operating variables. The incineration data base is intended to assist EPA Regional Offices and State environmental agencies in the review, assessment, and issuance of reasonable and responsible permits for regulated hazardous waste incineration facilities. Availability of such a data base would help to simplify and reduce the cost of permit and compliance testing and would assist in forming a sound technical basis for development and promulgation of detailed design, performance, and operating standards for hazardous waste incinerators in future revised regulations.

Important incineration operating and design parameters include waste material characteristics and properties, incinerator temperatures, excess oxygen concentrations, residence times, turbulence, and nozzle/atomizer type and configuration.

(4) To develop relationships for predicting the performance of incinerators of varying scale and design. Materials, including industrial wastes, that have been previously studied in laboratory-scale systems, or conversely, that have been incinerated

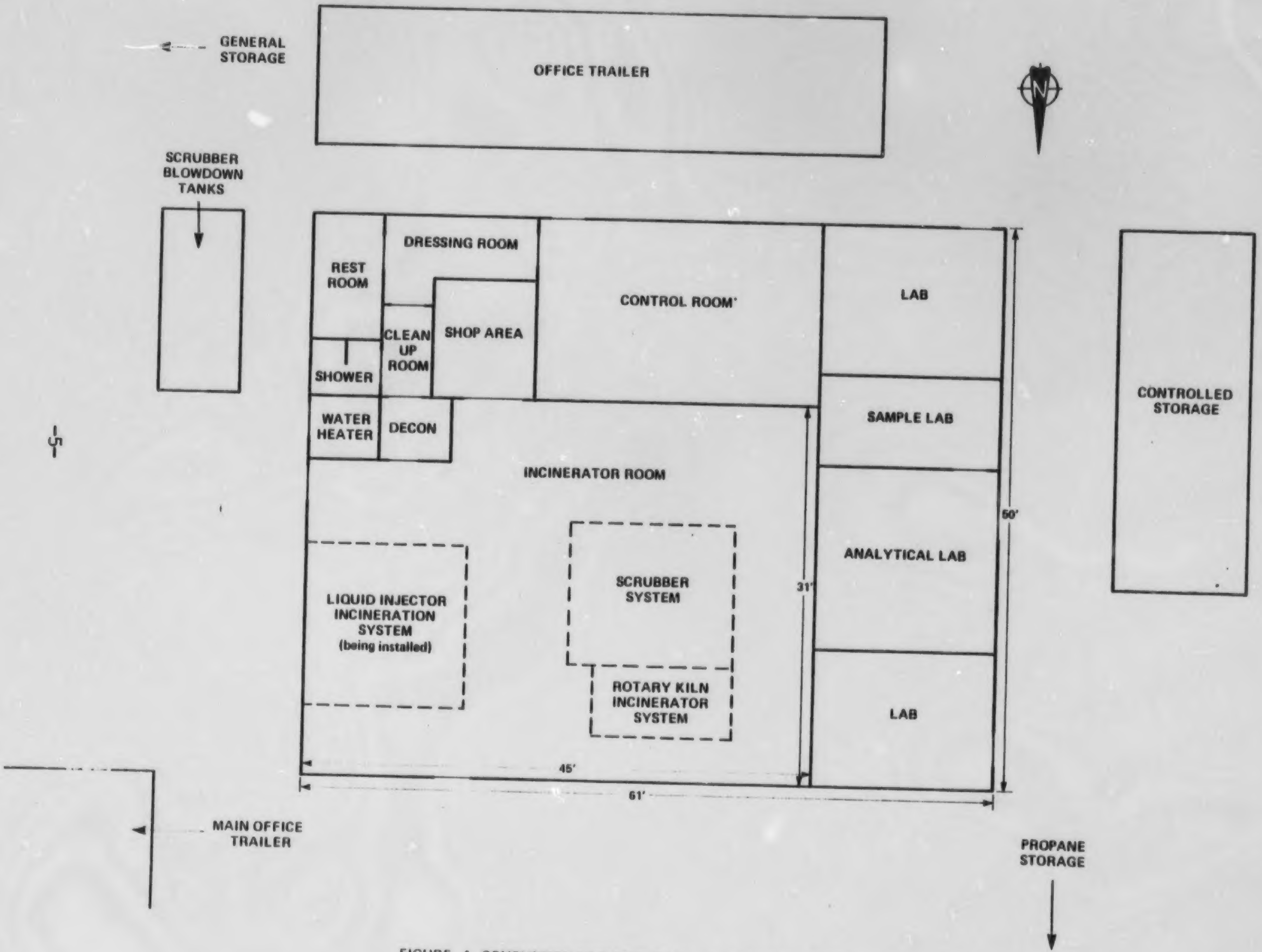
in full commercial-scale systems, would be studied at the pilot scale to assist in the understanding of scaling parameters and laws. Ongoing laboratory research efforts outside of the CRF program are developing data on thermal decomposition behavior, kinetics, PIC formation, and flame oxidation behavior on priority POHCs and compounds. Performance data are also being collected on full-scale incinerators and other thermal destruction processes, with emphasis upon those waste materials containing the priority POHCs. In some cases, POHCs (particularly carbon tetrachloride and trichloroethylene) have been "spiked" into the wastes tested to allow eventual intercomparison of full-scale, pilot-scale, and laboratory-scale performance data.

To the extent possible, the CRF will also attempt to obtain test quantities of selected hazardous wastes which are being tested in permit trial burns by incinerator owner/operators. Parametric testing of these same wastes in the CRF pilot-scale incinerators will be used to compare performance with the full-scale tests, to examine performance scale-up criteria and evaluate the significance and applicability of pilot-scale performance data.

FACILITY DESCRIPTION AND CHRONOLOGY

The USEPA Combustion Research Facility (CRF) is located on the campus of the National Center for Toxicological Research at Jefferson, Arkansas (near Pine Bluff). The general layout of the CRF showing the placement of the incineration systems is in Figure 1. The main building is shown in perspective, highlighting the high-bay incineration room, in Figure 2. The CRF is housed in a 3000 ft^2 concrete block building containing an incinerator room with an area of approximately 1400 ft^2. In addition, the facility contains a control room, analytical laboratories, instrument laboratory and a small office space. Support facilities are housed in several trailers located adjacent to the CRF.

Work on the CRF Program was initiated by Versar Inc. under Contract No. 68-03-3128 in April, 1982. Initial activities included planning for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DRESSING ROOM
CONTROL ROOM'
LAB
CLEAN UP ROOM
SHOP AREA
SHOWER
WATER HEATER
DECON
SAMPLE LAB
CONTROLLED STORAGE
INCINERATOR ROOM
50'
ANALYTICAL LAB
SCRUBBER SYSTEM
31'
LIQUID INJECTOR INCINERATION SYSTEM (being installed)
ROTARY KILN INCINERATOR SYSTEM
LAB
45'
61'
MAIN OFFICE TRAILER
PROPANE STORAGE

FIGURE 1 COMBUSTION RESEARCH FACILITY, GENERAL LAYOUT

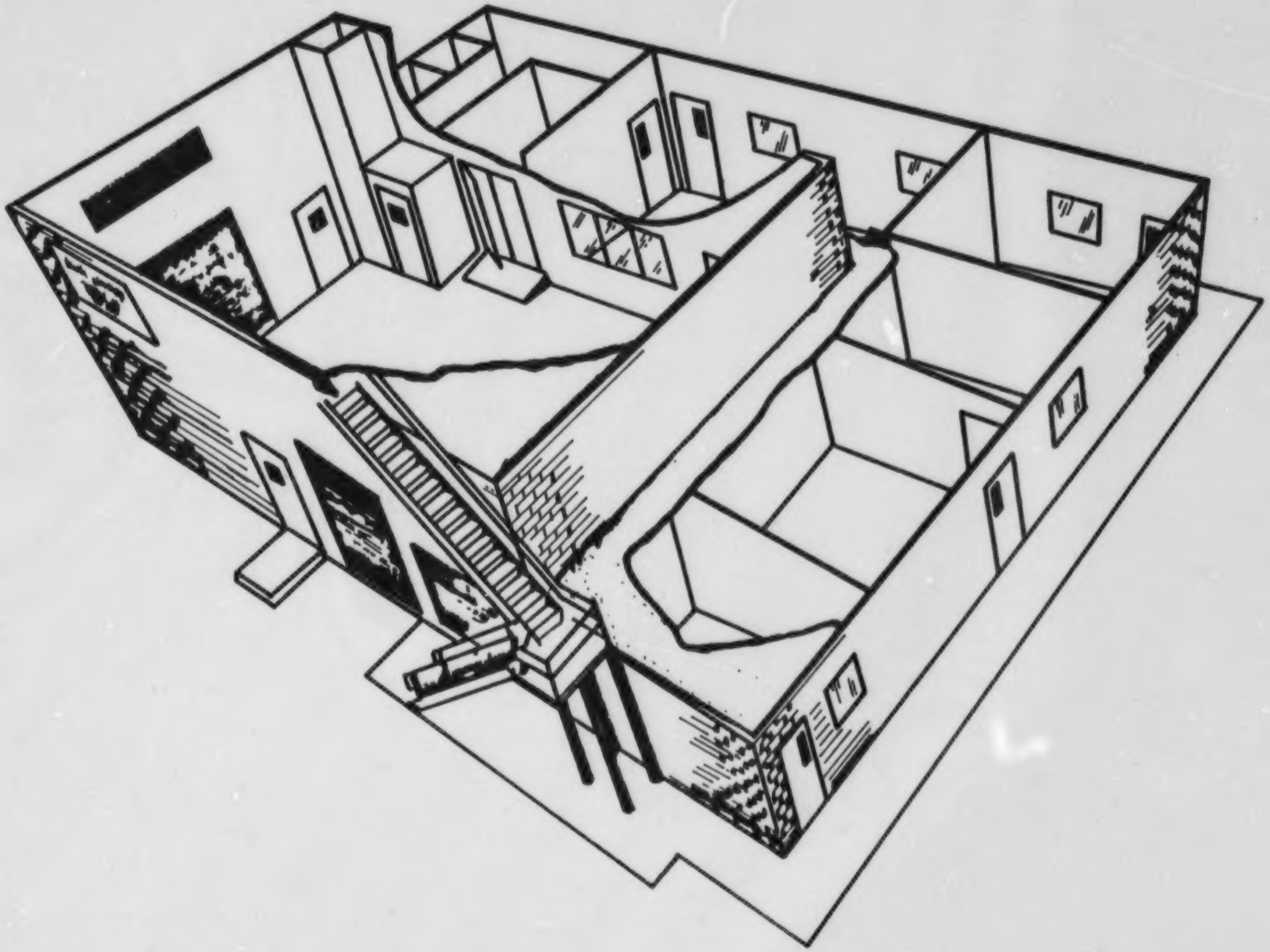


FIGURE 2
ARTIST RENDERING OF CRF CUTAWAY SHOWING
LABORATORIES AND INCINERATOR ROOM

the transport of the incinerator system to the CRF, development of the Health and Safety Manual, and establishment of the QA/QC Program Plan. The facility was occupied by Versar in July, 1982. At present, the CRF staff (including 8 professionals, 2 technicians and an office staff of 2) numbers 12 full-time personnel plus one part-time maintenance person.

A general chronology of major program events during the past two years is displayed in Table 1.

At the present time, the technology that is available at the CRF is a pilot scale rotary kiln with afterburner and an air pollution control system consisting of a variable throat venturi, wetted elbow and packed tower scrubber. In this section a brief description of each of these components will be presented; a more detailed discussion including detailed piping and instrumentation diagrams (P and ID) of the facility is contained in Section 2. The addition of a liquid injection incinerator, as indicated in Figure 1, is presently underway.

DESCRIPTION OF ROTARY KILN SYSTEM

An overall view of the rotary kiln system at the CRF is shown on Figure 3, and a photograph of the kiln feed face is presented as Figure 4. The physical properties of the kiln are listed in Table 2. The present configuration of the kiln is such that the waste feed is counter-current to the primary burner. The burner is fitted with an in-line Validyne Engineering Model 11-1-1000 propane meter. The primary combustion air is monitored by an in-line pitot. The kiln temperature is measured using a thermocouple (shielded) at the feed face. Additional monitoring equipment on the kiln includes the ability to monitor the combustion gases for both composition and flow rate. The combustion gases are monitored for CO, CO_2 and O_2 using an on-line Bendix Combustion Gas Analyzer. The residual organic compounds within the kiln transfer duct may be sampled for volatile compounds by extraction with collection in the Volatile Organic Sampling Train (VOST) or for high boiling compounds using the Modified Method Five (MM5) Train using a cooled XAD-2 resin for collections. Further information on these sampling systems is contained in Section 3.

TABLE 1. CHRONOLOGY OF EVENTS

15 July, 1982	Occupation of site by contractor personnel
15 September, 1982	Rotary kiln system assembly completed; analytical equipment ordered by EPA
1 November, 1982	Preliminary checkout tests of system completed; new ash collector system installed and other necessary upgrades initiated
15 December, 1982	Helium dilution system completed and calibrated
15 January, 1983	Analytical laboratory set up begun
15 Febuary, 1983	New APC system installed and checked out
15 March, 1983	Automated flue gas analysis system operational
28 April, 1983	Peer review of CRF Program
1 June, 1983	Operational shakedown initiated
28 July, 1984	Final engineering checkout; CRF adjudged fully operational
2 August, 1983	First hexachlorobenzene (POHC surrogate) test burn
10 September, 1984	Trichlorobenzene test series initiated
26 January, 1984	Chlorinated benzenes test series completed (34 tests)
10 February, 1984	Test series on synthetic wastes (EPA "Soups") initiated
15 June, 1984	Scheduled EPA Soup test burns completed; preparations begun for installation of liquid injection system

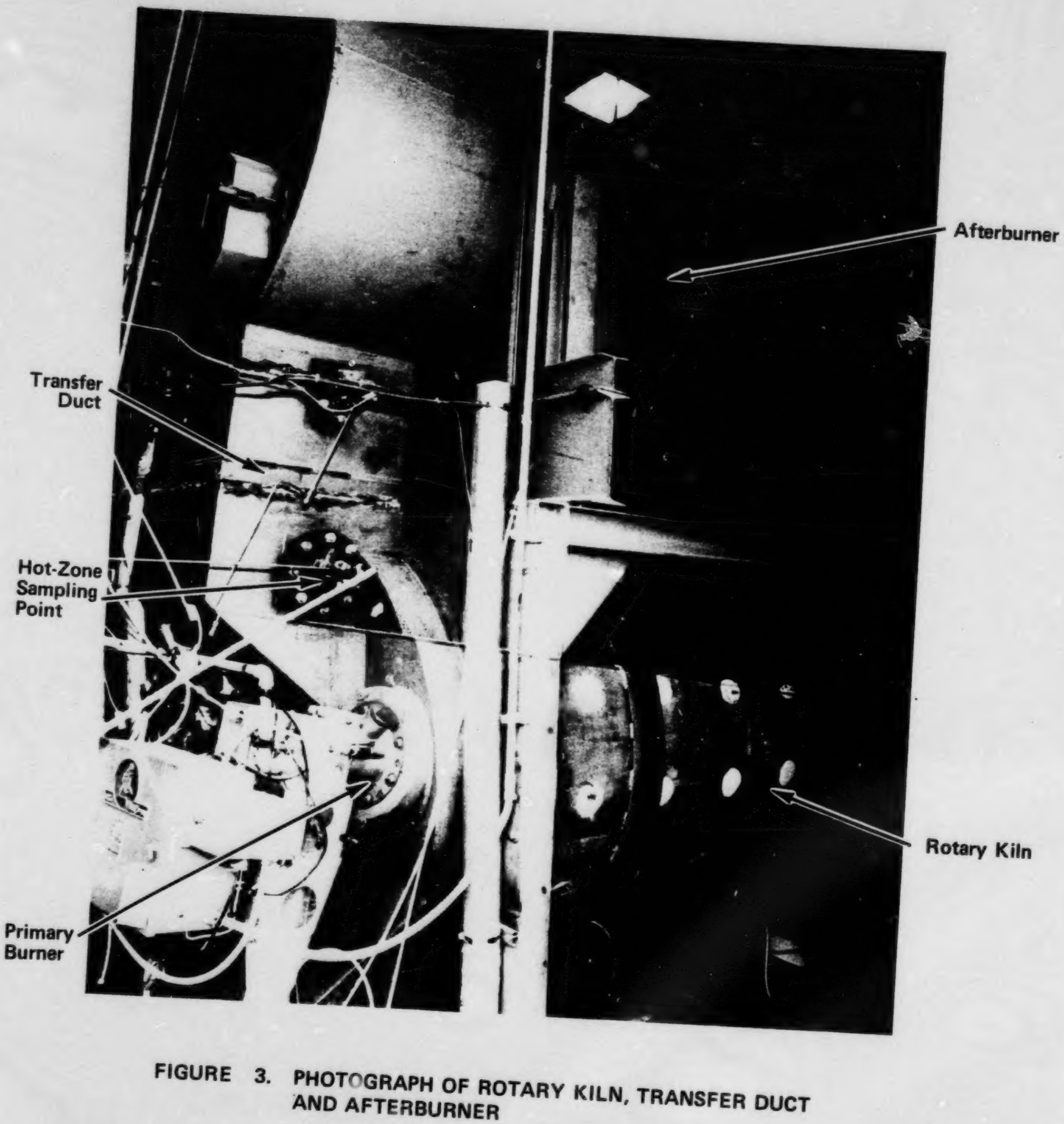
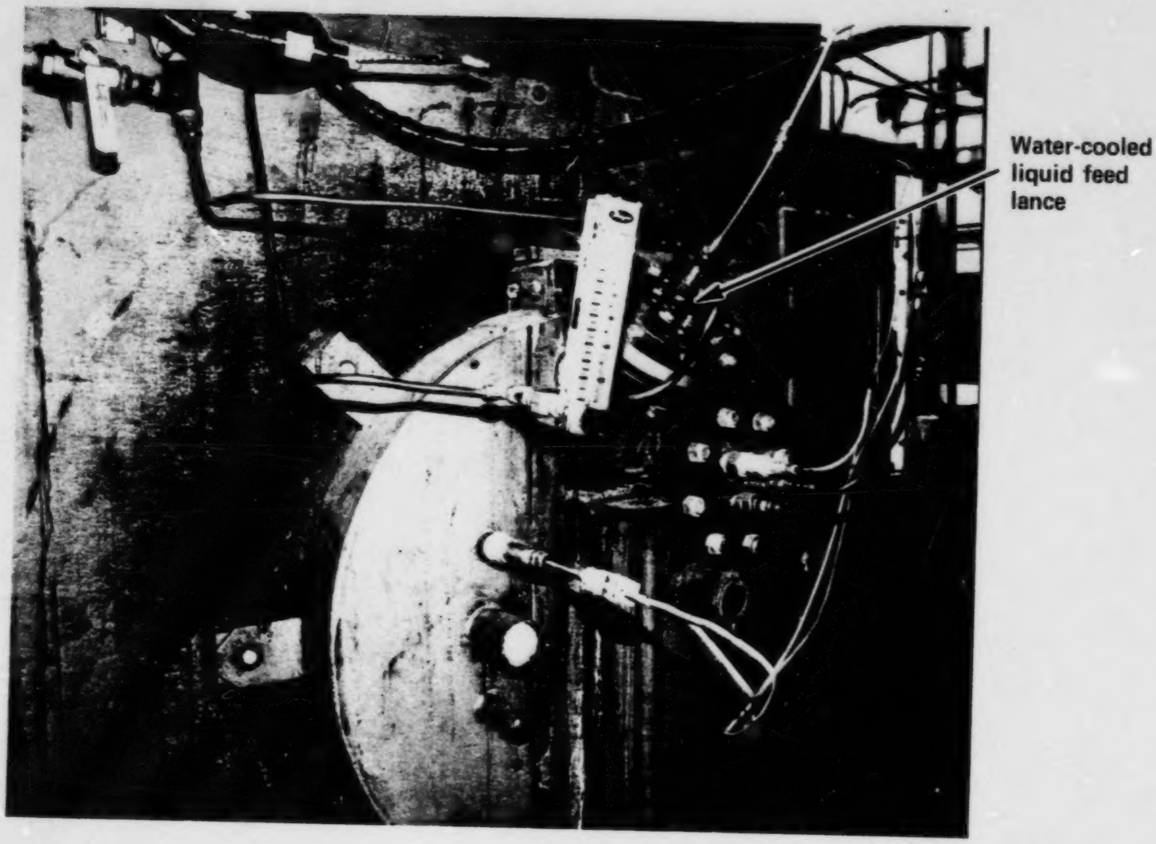

Afterburner
Transfer Duct
Hot-Zone Sampling Point
Rotary Kiln
Primary Burner

FIGURE 3. PHOTOGRAPH OF ROTARY KILN, TRANSFER DUCT AND AFTERBURNER



Water-cooled
liquid feed
lance

FIGURE 4. PHOTOGRAPH OF KILN FEED FACE

TABLE 2. PHYSICAL PROPERTIES OF THE CRF ROTARY KILN

Length	2.44 m (8 ft.)
Diameter	1.22 m (4 ft.)
Rotation	either direction range from 0.1 to 1.5 rpm
Construction	0.63 cm (0.25 in.) cold rolled steel
Refractory	12.7 cm (5 in.) castable refractory
Solids Retention Time	1 hr. (at 0.5 rpm)
Burner	Iron Fireman, model C-120-G-SMG rated at 1.8 MMBtu/hr
Primary fuel	propane
Feed System	
Liquids:	front face, water cooled lance with positive displacement pump
Semiliquids:	front face, water cooled lance with Moyno Pump
Solids:*	no provision available at this writing
Maximum operating temperature	900°C (1650°F)
Nominal capacity	200 lb/hour

* A newly designed feed face is presently being fabricated which will greatly enhance the feed capabilities of the kiln. The new face will have provisions for liquid and semi-liquid feeds through a variety of lance configurations and for solids or containerized solids using a ram feed device. It is anticipated that the installation of this new equipment will take place during 1984.

The combustion gases from the kiln are conducted through a refractory-lined transfer duct to the afterburner which is physically located above the kiln. The physical properties of the afterburner are listed in Table 3.

The afterburner temperature is measured using a shielded thermocouple located at the midsection of the chamber. Additional monitoring facilities consist of surface temperature, exit gas temperature, provisions for the determination of combustion gas composition and flow rate (essentially the same as is available for the kiln exit flue gases).

At this writing provisions are being made to change both burners using burners more readily adaptable to the purpose of the incinerator. At present, the feed rate of test materials in high heat value solvents is severely limited by the poor turn-down (<3) of the present burners.

UPGRADING OF ROTARY KILN INCINERATOR SYSTEM

In the Baseline Study of the EPA Incinerator conducted by Versar under Contract No. 68-03-3041, TASK SDV02, the need for a number of design modifications and experimental changes to the rotary kiln were identified. A significant portion of the effort expended by the CRF engineering staff during the first phase of the program was directed to these modifications. The major improvements were to:

- install new air pollution control system
- upgrade kiln rotary seals
- upgrade ash containment system
- upgrade on-line monitoring system
- upgrade on-line combustion gas analytical facilities
- upgrade POHC sampling activities and procedures
- redesign feed system capabilities

Each of the above elements will be discussed in succeeding paragraphs.

TABLE 3. PHYSICAL PROPERTIES OF THE CRF AFTERBURNER

Length	3.05 m (10 ft.)
Diameter	0.91 m (3 ft.)
Construction	0.63 cm (0.25 in.) cold rolled steel
Refractory	15.24 cm (6 in.) castable refractory
Retention time	depends on temperature and excess air
Burner	Iron Fireman, model C-120-G-SMG, rated at 1.8 MMBtu/hr
Primary fuel	propane
Maximum operating temperature	1200°C (2200°F)
Chamber volume	2.096M^3 (74ft^3)

One of the most significant upgrades made to the CRF incineration system was the replacement of the air pollution control system supplied by the original equipment manufacturer (OEM) with the kiln and afterburner. Preliminary tests at the CRF provided data required to size a new system, and a comparison of available integrated APC systems was performed. As a result, the Andersen 2000 system was selected as most nearly suitable to the needs of the CRF program. During installation of the new APC system, significant modification of the reinforced plastic ducting was performed in order to fit the system into the available incinerator room space, but observations with respect to both halogen acid emissions and particulate control have shown that the APC system is operating well within specifications.

The Andersen APC system, shown in Figure 5, consists of a variable throat wetted venturi, a wetted elbow, a packed spray column and a two stage mist eliminator. The general characteristics of these components are listed in Table 4.

In the OEM supplied kiln, there was little or no attempt to provide end seals for the kiln. At the burner end there was no shroud, while the feed face was provided with only a 1 inch shroud. The combined effect of the lack of provisions for sealing resulted in the inability to operate with less than approximately 250% excess air (partially contributed by the poor seal on the ash containment system). A partial seal has been effected by adding a 3 inch steel shroud on the burner end of the back plate and increasing that on the front face to 3 inches. In addition, a 1 1/2" diameter tube has been welded to the rotating shell on each end at a distance of 1 inch from each end shroud. A 5 inch wide (by 1/4" thick) piece of Toughtemp® cloth was then bolted to the shroud in such a manner as to overlap the tube. The seal was then affected by clamping the Toughtemp® over the tube, resulting in a sliding seal. This is not a complete solution but has been shown to be effective in that it is now possible to operate with excess air in the 60% range (of which some 15 to 20% is contributed by the primary combustion air to the burners).

The OEM supplied ash containment system was not appropriate for a number of reasons. First and foremost, the ash receiver was such that the collected

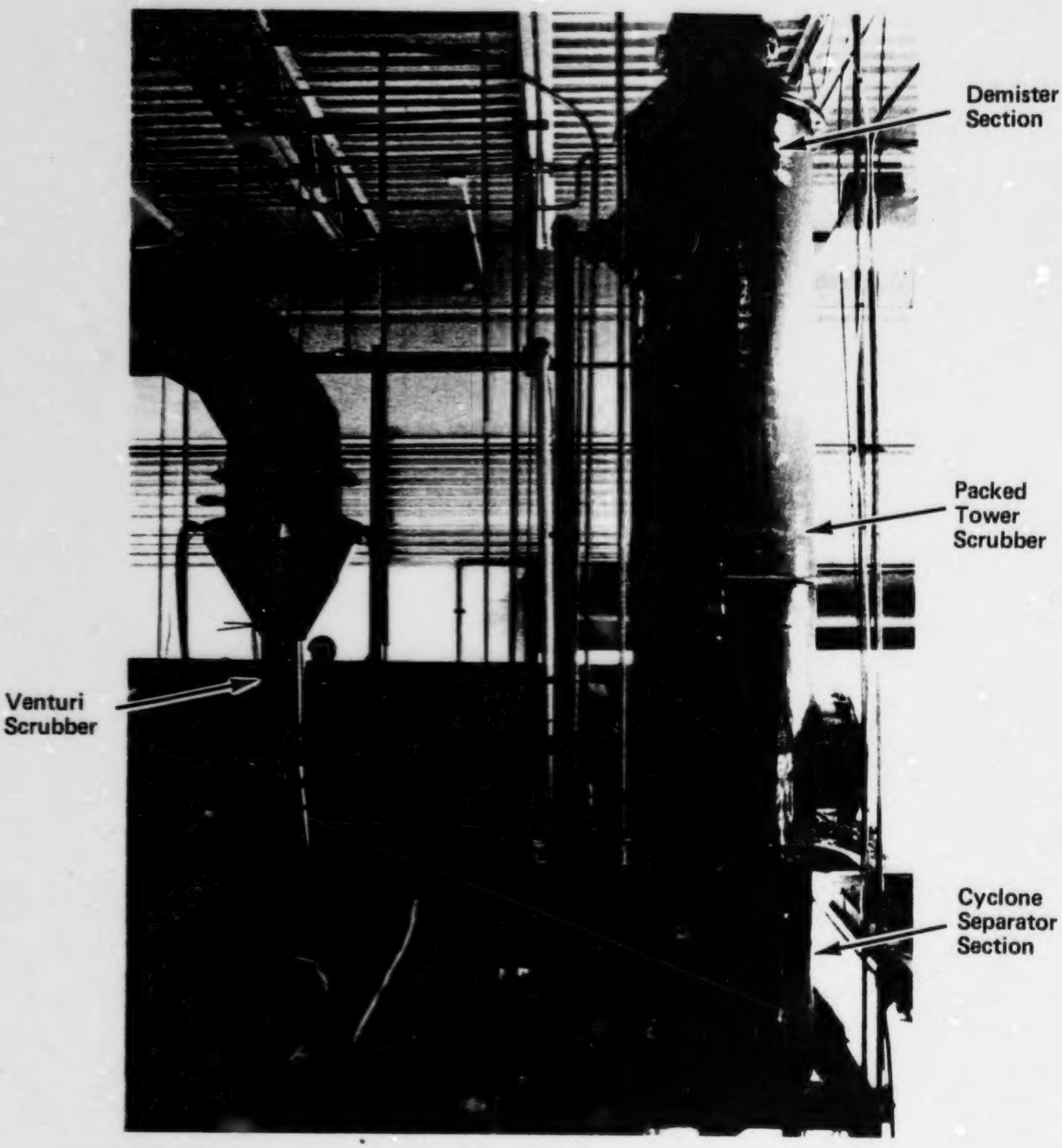

Demister Section
Packed Tower Scrubber
Venturi Scrubber
Cyclone Separator Section

FIGURE 5. AIR POLUTION CONTROL SYSTEM

TABLE 4. PHYSICAL PROPERTIES OF THE AIR POLLUTION CONTROL SYSTEM

System Size	Inlet gas flow rate of 106.8ACMM (3773 ACFM) at 1200°C (2200°F), at an absolute pressure of 14.660 psia.
Differential Pressures	Venturi - 30 in WG Packed tower - 4 in WG
Liquid Flows	Venturi - 20.4 gpm at 10 psig Tower - 30.6 gpm at 10 psig Blow down - variable from 2gpm to 5 gpm

ash could only be removed with a shovel, which could be hazardous to both the operator and the facility. Secondly, the physical arrangement was such that there appeared to be no way to seal the system; as mentioned above, this was responsible for a significant contribution to the infiltration of air. Both defects have been corrected by extending the rear stationary plate to form a refractory lined chamber sealed to the floor. The ash is collected in a sealable and readily removable drum which can then be properly disposed of.

Provisions have been made to perform and record all of the routine measurements shown in Table 5. Each of the parameters listed on Table 5, after suitable signal conditioning, is recorded every 5 minutes on an Omega line printer producing hard copy. The records are examined regularly to ascertain that there has been no significant change in the operational characteristics of the system components monitored. Further improvement (automation) is required to facilitate data recording and manipulation.

It was determined early in the program that a standard automatic on-line combustion gas analyzer system would be required for the CRF program, and that the Bendix on-line gas analyzer system would be suitable. The Table 5components of the Bendix system are listed in Table 6. The specific characteristics of the major instruments in the Bendix system are outlined in Tables 7 and 8.

It is informative to note the totality of monitoring activities which provide engineering data on system operation and incineration conditions. A complete list of the monitored parameters for engineering data, maintenance, and sampling is given in Table 9.

SUMMARY OF CHLORINATED BENZENES TEST BURN SERIES

By mid-July, 1983, the system and facility upgrades described previously had been completed, and the operational shakedown work showed that all of the CRF subsystems were fully operational. These subsystems are listed below:

Waste Material Storage and Feed Subsystem
Rotary Kiln and Afterburner Combustion Subsystem
Venturi Scrubber and Packed Tower Scrubber Air Pollution Control Subsystem

TABLE 5. ROUTINELY MONITORED SYSTEM PARAMETERS

temperature of blower motor casing (each burner)
temperature of blower motor bearing housing
temperature of kiln motor housing
temperature of kiln motor bearing housing
temperature of I.D. fan motor housing
temperature of I.D. fan motor bearing housing
temperature of kiln outer shell (several locations)
temperature of afterburner shell (several locations)
temperature of kiln pillow bearing housing (4 locations)
temperature of feed pump motor housing
temperature of feed pump motor bearing housing
line current to I.D. fan (each leg)
line current to burner blower fan (both burners)
line current to feed pump motor
line current to kiln drive motor
differential pressure across I.D. fan
absolute pressure within kiln at feed face
absolute pressure within kiln transfer line
input/output shell temperature at refractory lined elbow
propane temperature to each burner

TABLE 6. MAJOR COMPONENTS OF BENDIX ANALYZER*

Model 8903 Infrared Analyzer (CO, CO_2)
(dual beam)

Model 304 Oxygen Analyzer

Cam Timer Assembly

Two Stream Sample Handling System

Single Stream Sample Handling System

Two-Stream Teflon Sample Handling System

Probe Assembly (ceramic sheath)

Rack Assembly for Mounting Analyzers & Cam timer

Assembly Recorders and Panels

1) Two (2) Dual-Pen L & N Model 100
2) Two (2) Single-Pen L & N Model 100
3) Panel Mounting for all recorders

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*the available system is expected to be upgraded by the addition of several additional CO, CO_2 and O_2 monitors as well as the additional capability to monitor NO_x. This additional capability is anticipated to be available during the summer of 1984.

TABLE 7. SPECIFICATIONS - BENDIX MODEL 304 OXYGEN ANALYZER

Response Time:	10 to 90% in 2.6 seconds @ 290 ml/min. flow 10 to 90% in 4.0 seconds @ 115 ml/min. flow
Sensor Operating Temperature:	650°C ± 1%
Sensor Tubing Connections:	Inlet and Outlet Port 1/8" FPT
Accuracy:	1% of full scale
Interferences:	Combustibles typically cause a negative response equal to their oxygen demand
Stability:	0.2% O_2/24 hour period
Sensitivity:	1 volt/% O_2
Sample Flow (normal operation):	200 to 300 ml/min.
Resolution:	0.1% of O_2 reading
Flow Dependence:	1% of full scale from 100 to 600 ml/min.
Ranges:	0-10 and 0-25% O_2
Sensor Cable Length:	Standard - 50 feet Maximum - 500 feet
Noise:	0.25% of full scale
Power Requirements:	115 Vac 60 Hz 230 Vac 50 Hz
Recorder Output:	Standard - 0-10 volts Optional - 4-20 milliamps
Overall Dimensions:	Control Module - 5 1/2"H x 16 7/8"W x 13 1/2" D Sensor Module - 6 1/2" H x 6 3/4"W x 14" D
Alarms:	High and Low O_2 - adjustable
Weight:	Control Section - 11 lbs Sensor Housing - 12 lbs
Maximum Ambient Temperature:	Analyzer - 50°C Sensor - 50°C Effect of Temperature - .05% of full scale/°C maximum

TABLE 8. IR ANALYZER 8903 SPECIFICATIONS - CO AND CO_2 ANALYZER

Output Signal:	0-10V; output resistance 500 ohms
Minumum Detectable Sensitivity:	Less than 1% of full-scale
Noise:	Less than ± 0.5% of full-scale
Electronic Response Time:	2.9 seconds to 90% of full-scale
Zero Drift:	Less than ± 1% of full-scale per day
Span Drift:	Less than ± 1% of full-scale per day
Nonlinearity:	Less than 2% of full-scale
Precision:	± 2% of full-scale
Operating Temperature Range:	0-40°C (cabinet temperature controlled at 50°C)
Sampler Gas Flow:	0.1 liter/minute
Total Cross Interferences Error:	Less than 2% of full-scale
Influence of Gas Pressure Variations:	Less than 0.8% of measured value per 10 torr pressure difference
Power Requirements:	105-125 Vac, 50-60 hertz, 250 watts

TABLE 9. MONITORED PARAMETERS

ENGINEERING DATA

OPERATIONAL DATA	MEASUREMENT DEVICE
1) Kiln setpoint	Honeywell Dialapak
2) Kiln temp.-taken at feed face	K Thermocouple
3) Afterburner setpoint	Honeywell Dialapak
4) Afterburner temp.-taken at exit	R Thermocouple
5) Velocity head-kiln combustion air	Pitot tube/magnehelic
6) Velocity head-afterburner combustion air	Pitot tube/magnehelic
7) Kiln C_3H_8 consumption converter	Vol-O-Flow w/4-20 M A
8) Afterburner C_3H_8 consumption converter	Vol-O-Flow w/4-20 M A
9) Kiln C_3H_8 temperature	J Thermocouple
10) Afterburner C_3H_8 temperature	J Thermocouple
11) Kiln draft	Magnehelic
12) Afterburner temp-taken at middle of chamber	K Thermocouple
13) Temperature of air leaving bay (west fan)	J Thermocouple
14) Temperature of air leaving bay (east fan)	J Thermocouple
15) Kiln skin temp	J Thermocouple
16) Afterburner skin temp (2 locations)	J Thermocouple
17) Ambient wet & dry bulb temps	Sling Psychrometer
18) Stack temp	Dial Therm & J TC
19) AB Bendix & hotzone heated trace line entrance temp	J Thermocouple
20) Kiln & AB Bendix sample line exit temperature	J Thermocouple
21) Stack Bendix sample line entrance temperature	J Thermocouple
22) Stack Bendix sample line exit temperature	J Thermocouple
23) Kiln combustion air temperature	J Thermocouple
24) AB combustion air temperature	K Thermocouple

Note: Nos. 9-10, 12-16, and 18-24 automatically recorded in digital format.

MAINTENANCE DATA	MEASUREMENT DEVICE
1) Kiln pillow block temp # 1	J Thermocouple
2) Kiln pillow block temp # 2	J Thermocouple
3) Kiln pillow block temp # 3	J Thermocouple
4) Kiln pillow block temp # 4	J Thermocouple
5) Kiln drive motor temp	J Thermocouple
6) Kiln burner blower motor temp	J Thermocouple
7) Afterburner blower motor temp	J Thermocouple
8) ID fan motor temp	J Thermocouple
9) Refractory elbow skin temp # 1	K Thermocouple
10) Refractory elbow skin temp # 2	K Thermocouple

Note: The above are automatically recorded in digital format.

TABLE 9. (Continued)

SAMPLING DATA

PARAMETER	LOCATION	METHOD DATA	
particulate weight	stack	EPA Method 5	
particulate weight	kiln exit	EPA Method 5	
particulate weight	afterburner exit	EPA Method 5	
sample volume	stack	dry gas meters	analog readout
sample volume	kiln	dry gas meters	
sample volume	afterburner	dry gas meters	
combustion gas flow	stack	pitot and/or He dilution	
combustion gas flow	kiln exit	He dilution	
combustion gas flow	afterburner exit	He dilution	
combustion gas moisture content	stack	EPA Method 4	
combustion gas moisture content	kiln exit	EPA Method 4	
combustion gas moisture content	afterburner exit	EPA Method 4	
combustion gas temperature	stack	thermocouple	
combustion gas temperature	kiln	thermocouple	
combustion gas temperature	afterburner	thermocouple	
CO_2, CO, O_2	stack	continuous Bendix	
CO_2, CO, O_2	kiln	continuous Bendix	
CO_2, CO, O_2	afterburner	continuous Bendix	

I.D. Fan and Exhaust Stack Subsystem
Hot Zone Organic Sampling Subsystem
Analytical Chemistry Laboratory Subsystem
On-Line Measurement Subsystem
Control and Interlock Subsystem

With the major facility modifications in place (although future retrofits are planned to upgrade the system), a comprehensive system test series using hexachlorobenzene (HCB) and 1,2,4-trichlorobenzene (TCB) as surrogate hazardous waste materials was initiated to demonstrate the following objectives:

- Stable operation of each subsystem and of the complete integrated system, for extended testing times.
- Independent control of operating conditions for each test in accordance with the predetermined test plan.
- Acquisition and analysis of system reliability and engineering test data.
- Acquisition and analysis of exhaust stack analytical data on HCB and TCB as surrogate POHCs at a precision more than sufficient to determine Destruction and Removal Efficiency (DRE) to one part in 10^5.
- Development of preliminary information on PIC measurement methods and identification of potential PICs from HCB and TCB.

Hexachlorobenzene (HCB), which is considered to be among the most thermally stable organic compounds, was selected as the first candidate. Bench-scale (non-flame) thermal decomposition data were available for HCB. Further, it was adduced that, because of the presumed thermal stability, the range of possible products of incomplete combustion (PICs) from HCB was expected to be rather narrow which would result in simplifying the required analytical operations (or at least simplify the interpretation of these results). A further reason for selecting HCB lay in its relatively high boiling temperature (~330°C) which would result in low vapor pressure at the temperature of the liquid impinger system used in the EPA Method Five sampling train. This low effective vapor pressure should result in high collection efficiency. On the other hand, the poor solubility of HCB in most solvents necessarily led to the use of low feed rates in the HCB experiments. It was determined that toluene was the most appropriate solvent to serve as a carrier for the HCB. The combination of low HCB solubility (150gm HCB/gal toluene) and relatively high combustion heat of toluene (18000 Btu/lb) led to the selection of a feed rate of 100 gms HCB in 2.8 liters (3/4 gal) of toluene per hour.

The selection of 1,2,4-trichlorobenzene (TCB) as the second surrogate POHC to be tested was based on several factors. Obviously, since the TCB has chemical similarities to HCB but would not be expected to be as thermally stable, the choice of TCB offered the potential for studying a range of chemical stabilities. In addition, bench-scale thermal decomposition data were available for TCB, and it is more volatile than HCB but not to the extent that impinger collection efficiency would be seriously compromised. Toluene also was used as the carrier for TCB.

The general experimental protocol proposed for the chlorinated benzene series is presented in Table 10. All in all, a total of 34 test burns were conducted in the series covering the 19 tests on Table 10 plus additional background tests, duplicates, and additional burns designed to answer specific engineering questions. The date and purpose for each of the 34 tests, conducted between 28 July, 1983 and 26 January, 1984, are shown on Table 11.

Test data acquired at the USEPA Combustion Research Facility (CRF) may be classified into three types according to testing program objectives:

1. Data necessary to document the operating reliability and controllability of the rotary incineration system. These data include temperatures to which components and materials are subjected, the system pressure profile measurements relating to the control of combustion chamber negative pressure and of the venturi scrubber, and the temperatures, pressures, differential pressures, flowrates, liquid levels, and pH in the air pollution control subsystem.
2. Data necessary to document the operating conditions during each test, in terms of the physical dimensions and characteristics of the test incineration system as determined by design, installation, and operational modifications, in terms of the operator-controllable test

TABLE 10. CHLORINATED BENZENE PROTOCOL

EXP. NO.	POHC$^{(1)}$ IDENTITY	T_{AB} (°C)	T_k (°C)	FEED RATE (kg/hr)	SAMPLING$_{(2)}$ POSITIONS	REMARKS
1.	Propane	1093	879	~59	(a),(b)	Background
2.	Propane Toluene	1093	871	~59 2.43	(a),(b)	Background
3.	Propane Toluene	982	871	~56 2.43	(a),(b) (a),(b)	Background
4.	Propane Toluene	871	760	~50 2.43	(a),(b) (a),(b)	Background
5.	Propane Toluene	871	760	~48 2.43	(a),(b)	Failure Mode-AB burner shut off 2 min. every 15 min.
6.	Propane Toluene HCB	1093	871	~59 2.43 0.10	(c)	HCB fed as solution in Toluene
7.	Propane Toluene HCB	982	760	~56 2.43 0.10	(c)	HCB fed as solution in Toluene
8.	Propane Toluene HCB	810	760	~46 2.43 0.10	(c)	HCB fed as solution in Toluene
9.	Propane Toluene 1,2,4-TCB	1093	871	~59 2.43 0.10	(c)	1,2,4-TCB fed as Solution in toluene
10.	Propane Toluene 1,2,4-TCB	1093	871	~59 2.43 0.25	(c)	1,2,4-TCB fed as Solution in toluene
11.	Propane Toluene 1,2,4-TCB	1093	871	~59 2.43 0.5	(c)	1,2,4-TCB fed as Solution in toluene
12.	Propane Toluene 1,2,4-TCB	1093	871	~59 2.43 1.00	(c)	1,2,4-TCB fed as Solution in toluene
13.	Propane Toluene 1,2,4-TCB	1093	871	~59 2.43 0.10	(a),(b)	1,2,4-TCB fed as Solution in toluene

TABLE 10 (continued)

EXP. NO.	POHC(1) IDENTITY	T_{AB} (°C)	T_k (°C)	FEED RATE (kg/hr)	SAMPLING(2) POSITIONS	REMARKS
14.	Propane	982	871	~56	(a),(b)	1,2,4-TCB fed as Solution in toluene
	Toluene			2.43		
	1,2,4-TCB			0.10		
15.	Propane	871	982	~50	(a),(b)	1,2,4-TCB fed as Solution in toluene
	Toluene			2.43		
	1,2,4-TCB			0.10		
16.	Propane	871	982	~48	(a),(b)	Failure mode as above in Experiment 5
	Toluene			2.43	(a),(b)	
	1,2,4-TCB			0.10		
17.	Propane	1121	788 to 760	~46	(a),(b)	Failure mode in kiln
	1,2,4-TCB			4.0		
18.	Propane	1121	732 to 704	~46	(a),(b)	Failure mode in kiln
	1,2,4-TCB			4.0		
19.	Propane	1121	677 to 649	~46	(a),(b)	Failure mode in kiln
	1,2,4-TCB			4.0		

(1) Chemical(s) fed to simulate Principal Hazardous Organic Constituent (POHC).

(2) Position (a) is kiln transfer duct; (b) is AB transfer duct; (c) is stack.

TABLE 11. PURPOSE OF INDIVIDUAL EXPERIMENTS

Date	Experimental Purpose
7/28/83	Engineering Final Checkout
8/02/83	Initial HCB/Toluene Test Burn
8/04/83	Engineering for Mass/Energy Balance
8/10/83	HCB/Toluene Test Burn
8/12/83	HCB/Toluene Test Burn
8/17/83	Engineering Test Burn, He Dilution Test
8/19/83	HCB/toluene Test Burn
8/23/83	Engineering for Test of Cl^- and H_2O Measurements
8/25/83	HCB Background Test
9/01/83	1,2,4-TCB Test Burn
9/06/83	1,2,4-TCB Test Burn
9/08/83	1,2,4-TCB Test Burn
9/13/83	Engineering Test of Hot Zone Sampling
9/22/83	Background Test
9/26/83	Background Test
10/05/83	Engineering for Test of Cl^- and H_2O Measurement
10/11/83	Engineering Test for MM5 Hot Zone Sampling
10/17/83	Background Test
10 20/83	Engineering Test of the He Flow Measurements
10/26/83	Engineering Test for Recovery from Battelle Samplers
10/29/83	1,2,4-TCB Test Burn
11/01/83	Background for 1,2,4-TCB Hold Up in Scrubber
11/03/83	Background for 1,2,4-TCB Hold Up in Kiln or Afterburner
11/09/83	Engineering to Determine Feasibility of Simulated AB Flameout
11/11/83	1,2,4-TCB Test Burn-AB Failure Mode
11/16/83	Engineering-Kiln Failure Mode Study
11/18/83	1,2,4-TCB Kiln Flameout Simulation
11/22/83	1,2,4-TCB Test Burn
12/06/83	1,2,4-TCB Test Burn-Sampling Triplicate
12/09/83	Engineering-Mass/Energy Balance
12/13/83	Background from 1,2,4-TCB Tests
1/13/84	1,2,4-TCB Test Burn
1/24/84	Engineering Test/1,2,4-TCB Test Burn
1/26/84	HCB Test Burn

conditions, and in terms of engineering parameters not directly controllable but resulting from combinations of controllable test conditions and predetermined test article configuration characteristics.

3. Data necessary to determine the Destruction and Removal Efficiency (DRE) for POHCs across the entire rotary kiln incineration system, the Destruction Efficiency (DE) for each of the two combustion chambers, and the identification and quantification of PICs. The measurements for these determinations include the characterization of the waste feed material, quantification of the waste material feed rate, the chemical analysis of time-integrated samples (at known sampling rates) taken from the stack and from hot zones downstream from each combustion chamber, and the measurement of total flow rate in the stack and at each hot-zone sampling point.

The first and second types of data described above were collected for each of the tests performed. Reduction, analysis and interpretation for these types was limited to data from ten days of testing because of the magnitude of the dta base from the entire series. The engineering data are presented and discussed in Section 2.

Sampling and analytical data relating to POHC destruction and PIC identification in the tests are presented and discussed, together with the methodologies used, in Section 3.

As seen from the comparison of Tables 10 and 11, there were a number of tests performed to investigate specific engineering or technical questions, including investigations of helium dilution measurements, failure mode simulation, and sampling techniques. Results of these tests and discussion of the results are presented in Sections 4, 5 and 6.

SECTION 2

ENGINEERING TEST DATA FROM THE CRF ROTARY KILN SYSTEM

SUMMARY AND CONCLUSIONS

A total of 57 individual measurements of engineering data are routinely performed during the course of each CRF test burn. Of these, 22 measurements monitor the operation of the caustic scrubbing air pollution control subsystem, and 9 monitor the mechanical operating reliability of the kiln combustor.

The remaining 26 engineering measurements document the conditions of fluid flow, stoichiometry, material balances, heat balances, and thermal gradients within the incineration system, and are the subject of this volume of this report. The incinerator operating characteristics derived from these 26 engineering measurements, together with the DRE, DE, and PIC results obtained from sampling and chemical analysis, form the data base ultimately leading to explaining and predicting incinerator performance, reliability, and controlability.

This section of the report on CRF testing contains the pertinent details on CRF incineration equipment configuration, dimensions, and instrumentation. All of the algorithms, including instrument calibrations and thermodynamic and transport properties of the input and output fluids, are presented to document the details of reducing the test data and of deriving analytically-useful engineering parameters such as dimensionless ratios, coefficients, and rates from combinations of individual measurements. These data reduction procedures might now be automated.

Complete sets of the raw data for the 26 engineering measurements, and of the engineering parameters derived from these measurements, are presented in this report for ten of the first testing days (20 half-day test periods) of the chlorinated benzene test series. During this initial period, the data acquisition procedures and format for the 26 measurements evolved from the original (exclusively) manual recording from visual indicators, to the current system incorporating analog strip chart recordings of 5 measurements, digital logging at discrete times of 11 measurements, and manual recording at discrete times of 4 continuous measurements and of 6 intermittent and/or time-integrated measurements. Although significant progress has been made, additional changes are clearly indicated to improve the precision of the data acquisition process with respect to time-synchronization of diverse data sources, and to expedite the transition from a labor-intensive to an automated system.

Data taken at discrete times in 20 half-day runs for 14 continuous measurements afforded a measure of how well steady-state test conditions were maintained, for correspondence with the sampling requirements of time-integrated analytical results over intervals of one or more hours. For all except the kiln pressure measurement, the relative standard deviation for each of these parameters was no greater than 7.5 per cent, showing that the test conditions were reasonably close to steady state. Another observation made was that the afterburner conditions were apparently more stable over time than the kiln conditions.

Derivation of engineering parameters from alternate sets of independent primary measurements provided three opportunities to assess the internal consistency of the data set. One opportunity is in the alternate determination of the total flowrate of kiln exhaust gases by subtracting from the measured (via helium dilution) afterburner exhaust gas flow the contributions of measured afterburner propane and combustion air. The root-mean-square difference between the directly-measured (via helium dilution) value and the alternate value is 51 SCFM, which is 19 per cent of the overall mean. A sizable test-to-test variability may exist in one or more of the measured parameters. The alternate determination was adopted since this resulted in a lower standard deviation for the calculated air leakage rate into the rotary kiln (the mean value was 50 SCFM in either case).

A second comparison is that between the afterburner exhaust flowrate and the stack exhaust flowrate, both via helium dilution. On a moisture-free basis, these should be equivalent. The stack exhaust was systematically higher by 26 SCFM, which is 4 per cent of the overall mean value. Leakage of air into the scrubbing system could account for the observed bias.

A third comparison is between measured oxygen, carbon dioxide, and water vapor quantities in the stack gas and the comparable quantities calculated via combustion stoichiometry from measured feed rates to the system. The results showed large consistent differences between measured and calculated quantities: the measured O_2 quantity was greater than that calculated from feed quantities, but the measured CO_2 and H_2O quantities were less than those calculated from feed quantities. Either the propane fuel feed rates were actually 19 per cent lower than flowmeter measurements indicate, or air leakage occurred into the Bendix stack gas sampling system. Based upon an apparent error in stack sampling data for one test, the direct propane feed rate measurements were adopted, implying errors in stack sampling results for all tests.

The equilibrium among chlorine species (HCl, Cl_2, and Cl•) was determined using thermodynamic data at elevated temperatures. For all the runs, HCl accounts for greater than 99.8 per cent of all the chlorine under the conditions in the rotary kiln. Under the higher-temperature conditions in the afterburner, HCl accounts for greater than 98.8 per cent of all the chlorine. Almost all of the chlorine not present as HCl is in the form of the free-radical Cl• rather than as molecular chlorine.

Mass flow data and measured temperatures were used to derive other engineering quantities. Low linear velocities, 0.7 to 2.4 feet per second, and high gaseous residence times, 2.9 to 9.5 seconds, exist in the rotary kiln combustion chamber. The linear velocities in the kiln-to-afterburner transfer duct are in the range of 4.8 to 16.0 feet per second, are 4.8 to 8.9 feet per second in the afterburner, and are 24 to 42 feet per second in the afterburner exhaust duct. The afterburner residence times range from 1.0 to 1.9 seconds, with an additional 0.2 to 0.3 seconds at high temperatures in the exhaust duct.

The Reynolds numbers in the kiln range from 2,300 to 6,700, which is in the transition zone between the laminar and turbulent flow regimes. Turbulence induced by the kiln burner would influence the kiln flow patterns. In the kiln-to-afterburner transfer duct, N_{Re} ranges from 5,100 to 14,800; coincidentally similar to that in the afterburner (7,800 to 13,100). Flow should be turbulent in this regime. Turbulent flow is expected in the afterburner exhaust duct, with Reynolds numbers ranging from 16,800 to 27,000.

The elevation head, the velocity head, the friction loss, and the total pressure drop in each item of equipment exposed to unquenched combustion gases were calculated. The total head losses were less than 0.0004 inches of water in the rotary kiln, and less than 0.011 inches of water in the afterburner. In the more constricted sections of the system, the total head losses were somewhat higher: 0.012 to 0.040 inches of water in the kiln-to-afterburner transfer duct, and 0.059 to 0.171 inches of water in the afterburner exhaust duct.

Using heat of formation and heat capacity data for the substances fed to the incineration system, the total input enthalpy was determined for each run. The enthalpies of the combustion gases at measured system temperatures were determined from data for each substance of heat capacity as a function of temperature.

The heat losses from the combustion gases were calculated by difference between the input enthalpy to each portion of the system and the enthalpy of the combustion gases in that portion. Almost half of the heat input to the rotary kiln is lost, while the heat losses to both halves of the afterburner together amount to abount one-fourth of the total input enthalpy. For the entire system to the midpoint of the afterburner exhaust duct, the average heat losses are about 37 per cent of the total system heat input. The heat fluxes were about 4,600 Btu/ft^2-hr for the kiln; about 3,500 Btu/ft^2-hr for the transfer duct and upstream half of the afterburner; and about 2,100 Btu/ft^2-hr for the downstream half of the afterburner plus the upstream half of the exhaust duct.

Scope and Objectives

The engineering data analysis is based solely upon data acquired in the initial testing (after the facility checkout period) at CRF, during the months of August and September 1983. Testing was conducted on ten days: August 17, 19, 23, and 25, and September 1, 6, 8, 13, 22, and 26. Each day of testing was treated as consisting of two consecutive but separate runs, consistent with the practice of acquiring independent stack samples for the early and later portions of the day. A total of 20 test runs was therefore included in this report. For several of the days, test conditions were intentionally changed between the early and later times. For all of the days, some pertinent test conditions inadvertently but measurably changed, attributable to the fact that true thermal equilibrium of the equipment exposed to hot combustion gases was (knowingly) not achieved during the 8-hour testing period. The most noticeable impact upon test conditions was a continuously decreasing flow with time of propane fuel and of combustion air, to maintain constant set-point gas temperatures in each of the two combustion chambers, as the incinerator insulation and structural shell became hotter (e.g., approached thermal equilibrium more closely).

The major objectives for this data analysis activity were:

1. To publish the reduced engineering test data, over the testing period covered, in a format suitable for futher analysis and also to serve as permanent documentation of test results.
2. To document those details of incineration equipment configuration (dimensions, instrumentation) needed for analysis of engineering data.
3. To document the procedures and details of the data reduction process, including instrument calibrations where appropriate, and to comment on the primary data acquisition and recording practices from the viewpoint of data reduction requirements.
4. To analyze the test data from the viewpoint of internal consistency, and to comment on apparent sources of uncertainties, especially where engineering parameters might be derived from alternate sets of independent primary measurements.

5. To estimate the levels of uncertainty in the primary test data and in derived parameters.

6. To document derived engineering parameters (e.g., dimensionless ratios and transfer coefficents) which might be useful in the future development of predictive relationships for incinerator performance.

Configuration of the CRF Rotary Kiln Incineration System

Figures 6, 7, and 8 are P and I Diagrams for (respectively) the waste feed and combustion subsystems, the caustic scrubber air pollution control subsystem, and the ID fan, exhaust stack, and sampling subsystems of the CRF rotary kiln incineration system.

Table 12 lists the dimensions of the major items of equipment upstream of the quenching and scrubbing operations. These include the rotary kiln, the transfer duct connecting the kiln to the afterburner, the afterburner chamber, the exhaust duct just downstream of the afterburner chamber, and the venturi inlet duct. Also included is the portion of the stack (see Figure 8) below the damper, which is a closed-end pneumatic capacitance rather than a through path for exhaust gases. Hot-zone sampling points S_1 and S_2 are (respectively) in the kiln-to-afterburner transfer duct and in the afterburner exhaust duct. Consequently, Table 12 separately lists the dimensions for the portions of each duct upstream and downstream of the sampling points.

Table 13 lists the instrumentation on the rotary kiln incineration system, with the instrumentation I.D. numbers relating to those on Figures 6, 7, and 8.

REDUCTION OF RAW TEST DATA

Moisture Content of Combustion Air

The dry bulb and wet bulb temperatures, θ_{DB} and θ_{WB}, °F, were measured with a psychrometer several times during each run. The percent relative humidity, RH, was determined from tables in Lange(1), although alternatively, psychrometric charts such as those in Perry(3) might have been used. The saturation value for absolute humidity at the measured dry bulb temperature, Hs, in grams per cubic meter, was determined from

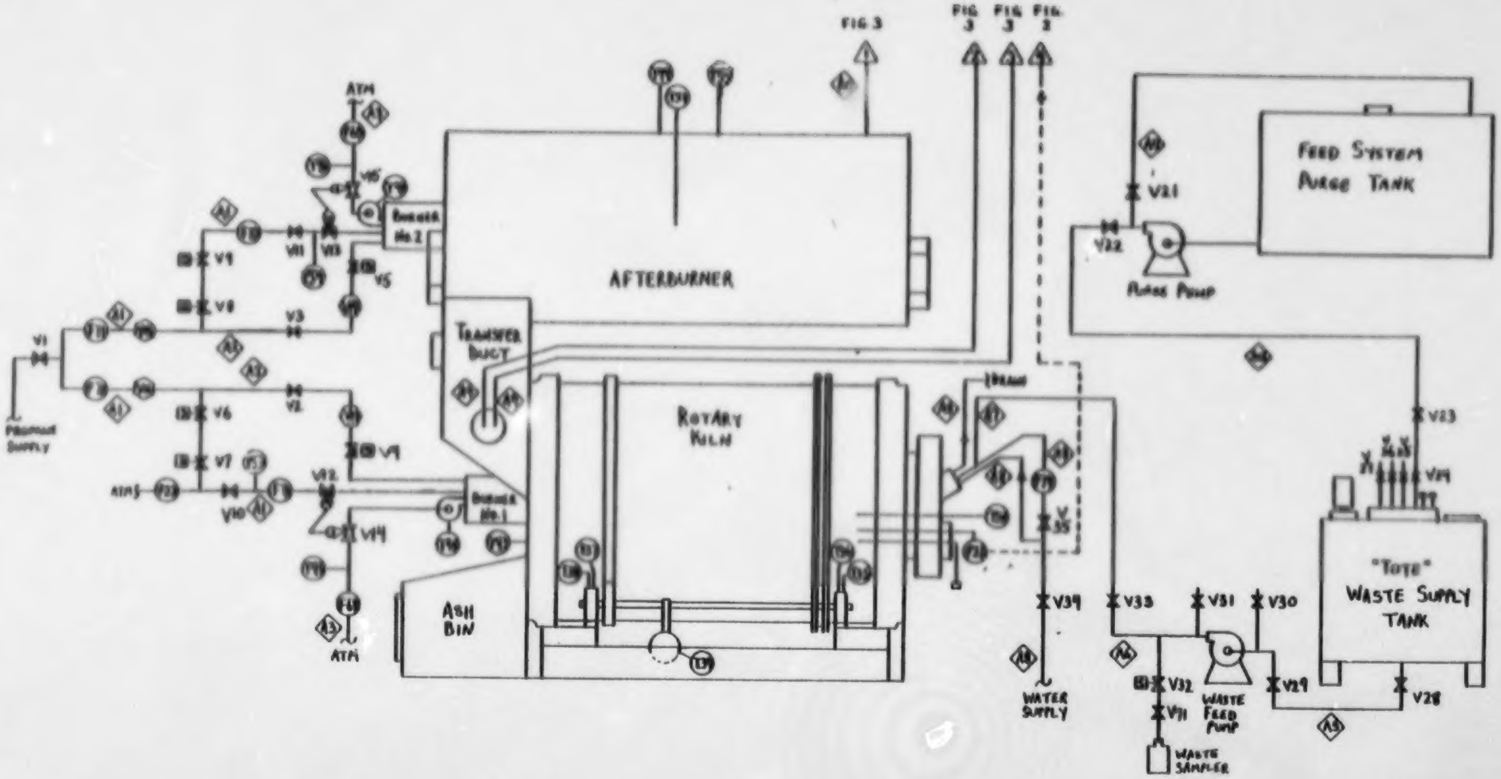
FIG 3
FIG 3
FIG 3
FIG 2
ATM
FEED SYSTEM PURGE TANK
V21
V22
PURGE PUMP
AFTERBURNER
BURNER No. 2
BURNER No. 1
TRANSFER DUCT
ROTARY KILN
ASH BIN
PROPANE SUPPLY
V1
V2
V3
V4
V5
V6
V7
V8
V9
V10
V11
V12
V13
V14
V15
ATMS
ATM
DRAIN
V35
V39
WATER SUPPLY
V33
V31
V30
V32
V11
WASTE SAMPLER
WASTE FEED PUMP
V29
V28
V23
V19
"TOTE" WASTE SUPPLY TANK

FIGURE 6. WASTE FEED AND COMBUSTION SUBSYSTEMS

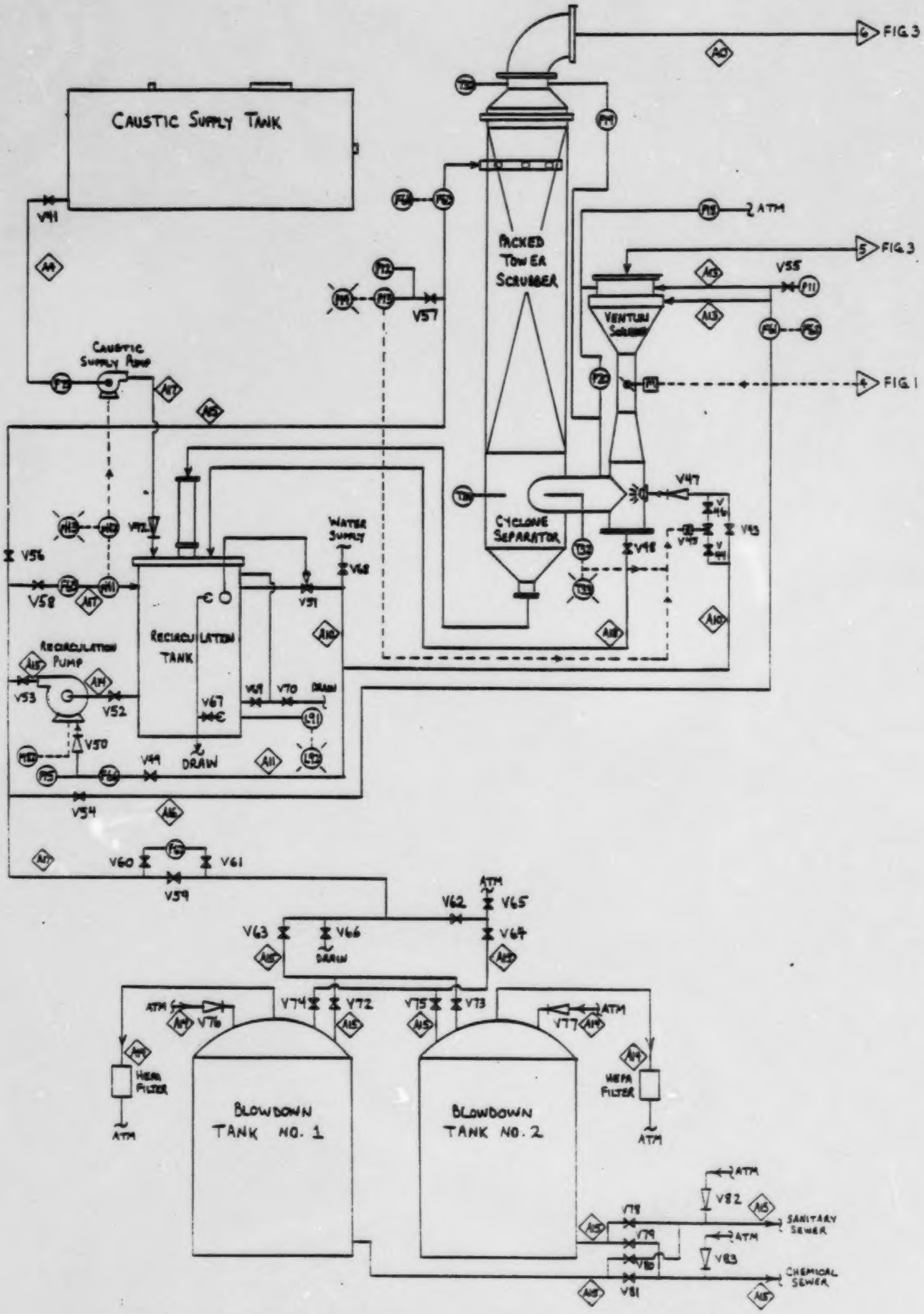
FIG 3
CAUSTIC SUPPLY TANK
V91
CAUSTIC SUPPLY PUMP
PACKED TOWER SCRUBBER
ATM
FIG 3
V55
V57
VENTURI SCRUBBER
FIG 1
V47
V46
V43
V45
V44
V48
CYCLONE SEPARATOR
WATER SUPPLY
V68
V92
V56
V58
V51
RECIRCULATION TANK
RECIRCULATION PUMP
V53
V52
V67
V69
V70
DRAIN
V50
V49
DRAIN
V54
V60
V61
V59
ATM
V62
V65
V63
V66
V64
DRAIN
ATM
V74
V72
V75
V73
V76
V77
ATM
HEPA FILTER
ATM
BLOWDOWN TANK NO. 1
BLOWDOWN TANK NO. 2
HEPA FILTER
ATM
ATM
V82
V78
SANITARY SEWER
V79
ATM
V80
V83
V81
CHEMICAL SEWER

FIGURE 7. CAUSTIC SCRUBBER AIR POLLUTION CONTROL SUBSYSTEM

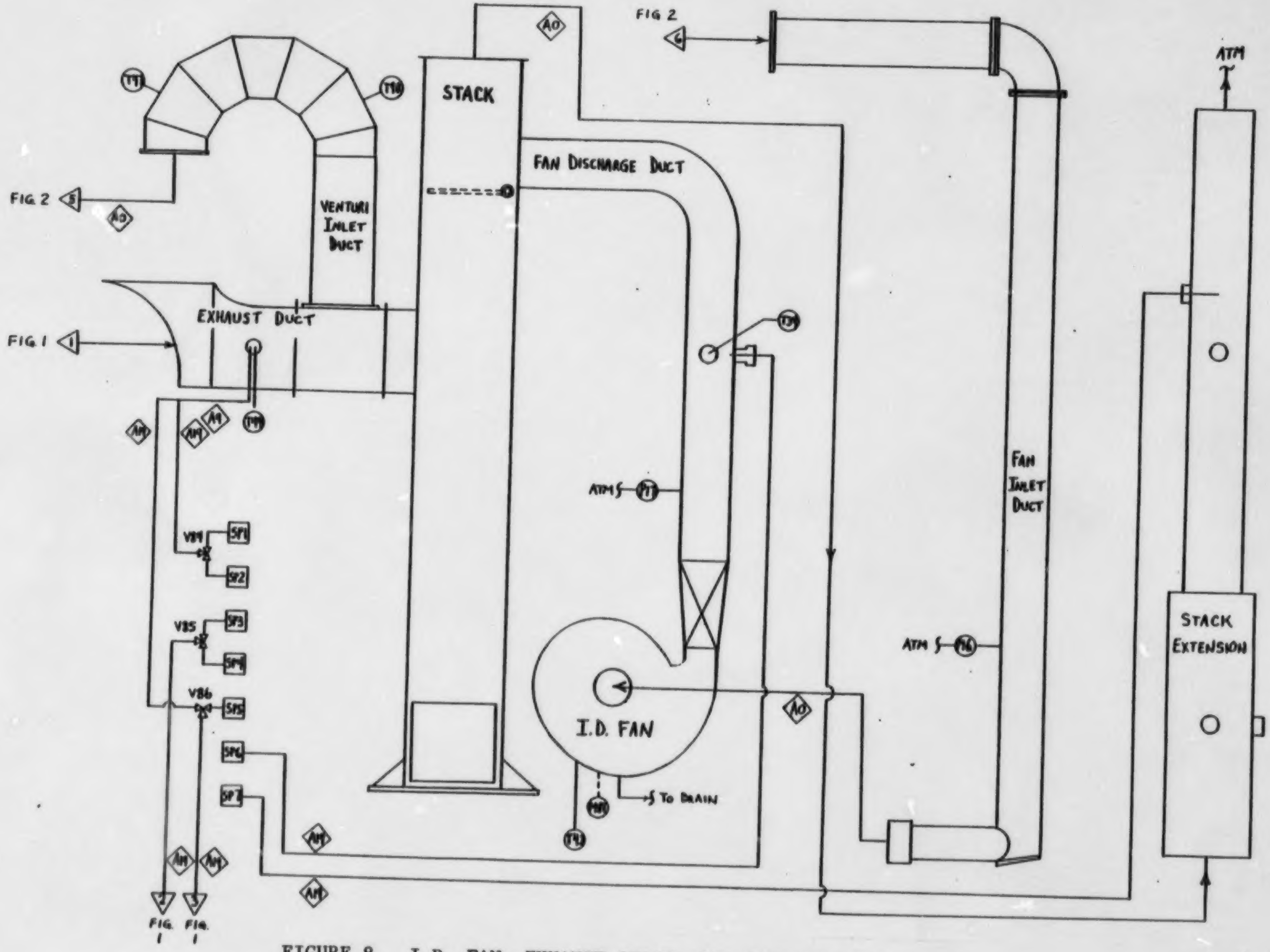
STACK
FAN DISCHARGE DUCT
VENTURI INLET DUCT
EXHAUST DUCT
FIG 2
FIG 2
FIG 1
FIG. 1
FIG. 1
ATM
ATM
ATM
FAN INLET DUCT
STACK EXTENSION
I.D. FAN
TO DRAIN
V84
V85
V86
SP1
SP2
SP3
SP4
SP5
SP6
SP7

FIGURE 8. I.D. FAN, EXHAUST STACK, AND SAMPLING SUBSYSTEMS

TABLE 12. DIMENSIONS OF EQUIPMENT EXPOSED TO UNQUENCHED COMBUSTION GASES

	Rotary Kiln	Transfer Duct Upstream of $S_1^{(2)}$	Transfer Duct Downstream of $S_1^{(2)}$	Afterburner Chamber	Exhaust Duct Upstream of $S_2^{(2)}$	Exhaust Duct Downstream of $S_2^{(2)}$	Venturi Inlet Duct	Stack Below Damper[3]
Nominal External X-Section, In.	60 Dia	32 x 23	32 x 23	48 Dia	28 x 28	28 x 22	16 Dia	30 x 30
Nominal Length, Inches	96	18	27	120	42	44	114	162
Nominal Shell Thickness, In.	0.25	0.25	0.25	0.25	0.25	0.25	0.125	0.25
Nominal Internal Insulation Thickness, Inches	6.0 (Feed) 4.5 (Disch)	4.5	4.5	4.5	4.5	4.5	1.0	0
Volume, Cubic Feet:								
Total Outside Envelope[1]	157.080	4.472	12.271	125.664	16.226	15.685	13.391	84.375
Steel Shell[1]	3.412	0.202	0.509	3.117	0.551	0.637	0.420	2.789
Refractory Insulation	62.517	3.072	7.309	48.103	9.619	9.549	2.727	---
Internal Free Space	91.151	1.198	4.453	74.444	6.056	5.500	10.244	81.586
Surface Area, Square Feet:								
Outer Shell Surface[1]	164.934	9.713	24.422	150.796	26.446	30.556	40.281	135.000
Internal Surface	115.492	4.595	14.179	108.982	16.135	18.333	35.232	132.750
Smallest X-Sectional Area, ft^2	13.100	1.986	1.986	8.084	2.250	1.500	1.050	6.043
Wetted Perimeter, ft	12.829	5.833	5.833	10.079	6.000	5.000	3.632	9.833
Hydraulic Diameter, ft[4]	4.085	1.362	1.362	3.208	1.500	1.200	1.156	2.458

Notes:
(1) Exclusive of Supports, Flanges, Fittings, etc.
(2) S_1 and S_2 are (respectively) the hot gas sampling points in the kiln-to-afterburner transfer duct and in the afterburner exhaust duct.
(3) The stack below the damper is a closed-end pneumatic capacitance rather than a through path for exhaust gases.
(4) Hydraulic Diameter = 4 x cross-sectional area/wetted perimeter

TABLE 13. INSTRUMENTATION

I.D.	Anderson 2000 I.D.	Type*	Description of Measurement	Instrument and Range
pH1	AT210	T	pH, Recirculating Liquor to Recirculation Tank	Great Lakes, 2-12 pH
pH2	AIC208	R	pH, Recirculating Liquor to Recirculation Tank	Great Lakes, 2-12 pH
pH3	AAL209	A	pH, Recirculating Liquor to Recirculation Tank	Great Lakes, 2-12 pH
P11	PI220	L	Pressure, Scrubbing Liquor to Venturi Inlet	Diaphragm Guage, 0-60 psig
P12	PI204	L	Pressure, Scrubbing Liquor to Packed Tower Inlet	Diaphragm Guage, 0-60 psig
P13	PSL205	T	Pressure Switch, Scrubbing Liquor to Packed Tower Inlet	0-50 psig
P14	PAL206	A	Pressure, Scrubbing Liquor to Packed Tower Inlet	
P15	PI203	L	Pressure, Seal Water to Recirculation Pump	0-100 psig
P16	PDI110	R	Differential Pressure, Fan Inlet Duct to Atmosphere	Dwyer #2050
P17	PDI112	R	Differential Pressure, Fan Outlet Duct to Atmosphere	Dwyer #2005
P18	PDIC101	T	Differential Pressure, Venturi Inlet to Atmosphere	Dwyer #3310
P19	PDI108	R	Differential Pressure, Packed Tower Inlet to Packed Tower Outlet	Dwyer #2006
P20	PDI102	R	Differential Pressure, Venturi Inlet to Venturi Outlet	Dwyer #2050
P21	-	R	Pressure, Rotary Kiln Combustion Gas	0-0.50 inches H_2O
P22	-	L	Differential Pressure Propane to Burner No. 1	±15 inches H_2O
T31	TI104	L	Temperature, Venturi Outlet Gas, in Cyclone Separator	0-300°F
T32	TSH105	T	Temperature, Venturi Outlet Gas, at Inlet to Cyclone	
T33	TAH106	A	Temperature, Venturi Outlet Gas	
T34	TI113	L	Temperature, Fan Outlet Duct	Dial Thermometer, 50-300°F
T35	-	R	Temperature, Kiln Roller Bearing #3 (Front Right)	Analog Omega Type J, 0-500°F
T36	-	R	Temperature, Kiln Roller Bearing #1 (Front Left)	Analog Omega Type J, 0-500°F
T37	-	R	Temperature, Kiln Roller Bearing #2 (Rear Left)	Analog Omega Type J, 0-500°F
T38	-	R	Temperature, Kiln Roller Bearing #4 (Rear Right)	Analog Omega Type J, 0-500°F
T39	-	R	Temperature, Kiln Drive Motor	Analog Omega Type J, 0-500°F
T40	-	R	Temperature, Burner No. 1 Fan Motor	Analog Omega Type J, 0-500°F
T41	-	R	Temperature, Burner No. 2 Fan Motor	Analog Omega Type J, 0-500°F
T42	-	R	Temperature, I.D. Fan Motor	Analog Omega Type J, 0-500°F
T43	-	R	Temperature, Kiln Backface Skin	Analog Omega Type K, 0-1000°F
T44	-	R	Temperature, Afterburner Skin (Side)	Analog Omega Type J, 0-800°F
T45	-	R	Temperature, Combustion Air to Burner No. 1	Analog Omega Type J, 0-300°F
T46	-	R	Temperature, Combustion Air to Burner No. 2	Analog Omega Type J, 0-300°F
T47	-	R	Temperature, Venturi Inlet Duct Entrance Section Skin	Analog Omega Type K, 0-1500°F
T48	-	R	Temperature, Venturi Inlet Duct Discharge Section Skin	Analog Omega Type K, 0-1500°F
T49	-	R	Temperature, Afterburner Exhaust Duct Gas	Analog Omega Tyep K, 0-2500°F

TABLE 13. INSTRUMENTATION (Continued)

I.D.	Anderson 2000 I.D.	Type*	Description of Measurement	Instrument and Range
T50	-	R	Temperature, Kiln Combustion Gas	Type K, Honeywell Dialapak prop. controller, 0-2400°F
T51	-	R	Temperature, Afterburner Combustion Gas	Type R, Honeywell Dialapak prop. controller, 0-3000°F
T52	TI109	L	Temperature, Packed Tower Exhaust Gas	
T53	-	R	Temperature, Propane to Burner No. 1	Type J, 0-500°F
T54	-	R	Temperature, Propane to Burner No. 2	Type J, 0-500°F
T55	-	R	Temperature, Afterburner Skin (Top)	Type K, 0-1000°F
F61	FE218	T	Flow Indicator, Scrubbing Liquor to Venturi Inlet	
F62	FI219	R	Flow Indicator, Scrubbing Liquor to Venturi Inlet	Signet, Paddlewheel, 0-120 GPM
F63	FE212	T	Flow Indicator, Scrubbing Liquor to Packed Tower Inlet	
F64	FI213	R	Flow Indicator, Scrubbing Liquor to Packed Tower Inlet	Signet, Paddlewheel, 0-200 GPM
F65	FI214	L	Flow Indicator, Recirculating Liquor for pH Probe	Sight Flow Indicator
F66	FI202	L	Flow Indicator, Seal Water to Recirculation Pump	Midwest Paddlewheel
F67	FI207	L	Flowrate, Disposal from Recirculation Tank	Rotameter, 0-5 GPM
F68	-	R	Flowrate, Combustion Air to Burner No. 1	Pitot Tube, 0-1.0 inches H_2O Velocity Head
F69	-	R	Flowrate, Combustion Air to Burner No. 2	Pitot Tube, 0-1.0 inches H_2O Velocity Head
F70	-	L	Total Flow, Propane to Burner No. 1	Totalizing Gas Meter
F71	-	L	Total Flow, Propane to Burner No. 2	Totalizing Gas Meter
F72	-	R	Flowrate, Main Propane to Burner No. 1	Laminar Venturi (CME), 35 SCFM Propane
F73	-	R	Flowrate, Main Propane to Burner No. 2	Laminar Venturi (CME), 35 SCFM Propane
F74	-	L	Flowrate, Injection Water to Waste Feed Port	Rotameter, 0-12 gph
F75	-	L	Flow Indicator, Caustic Feed to Recirculation Tank	Ball, Integral With Pump
M81	MS111	R	Motor On, ID Fan	
M82	HS201	R	Motor On, Recirculation Pump	
L91	LSL215	T	Low Level Indicator, Recirculation Tank	
L92	LAL216	A	Low Level Alarm, Recirculation Tank	

*L - Local Instrument
R - Remote-Reading Instrument
T - Signal Transmitter
A - Alarm and Annunciator

Lange(2). The calculation for W, the volume percent moisture in the combustion air, incorporated a temperature correction from θ_{DB} to 32°F for specific volume:

$$\text{W, vol \% Moisture} = \frac{\text{RH, \%} \times H_s, \frac{g}{m^3} \times 0.022414 \frac{m^3}{\text{g mole}}}{18.016 \frac{g}{\text{g mole}} \times \frac{459.7 + 32}{459.7 + \theta_{DB}}}$$

$$W = 1.2441 \times 10^{-3} \times RH \times H_s \times \frac{459.7 + \theta_{DB}}{459.7 + 32}$$

Table 14 contains the raw measurements and the corresponding derived quantities.

Process Flowrates from Helium Tracer Analysis

Total flowrate at several points in the incineration system is determined by a helium tracer method. A known quantity of helium, 5 standard liters per minute (0.17658 standard cubic feet per minute), is injected into the combustion air to the kiln burner. Gas samples, withdrawn from the kiln-to-afterburner transfer duct (sampling point i=K), from the afterburner exhaust duct (i=AB), and from the final stack (i=S), are analyzed for helium concentration, to give a measure (by dilution of the injected helium) of the total volumetric flowrate at these locations. Since moisture is removed from each gas sample prior to helium analysis, the results are in terms of dry (moisture-free) volumetric flowrate.

The GC instrument for determining helium concentration is calibrated using a standard gas of 5 parts helium in 9,000 parts of nitrogen/helium mixture, with a measured peak height response of Z_{STD} mm. If the corresponding peak height for a (dried) process gas sample is $Z_{i,t}$ mm, from sampling point i at clock time t, then the corresponding moisture-free process gas flowrate is:

$$Q_{i,t}, \text{SCFM} = \frac{0.17658}{\frac{5}{9,000} \times \frac{Z_{i,t}}{Z_{STD}}} = 317.844 \frac{Z_{STD}}{Z_{i,t}} .$$

TABLE 14. HUMIDITY DATA AND CALCULATED QUANTITIES

Test Date	Run	Clock Time	θ_{DB} °F	θ_{WB} °F	RH %	H_s g/m^3	W %
0817	1	0900	82	76	76	26.9	2.80
		0930	85	77	70	29.5	2.96
		1000	85	77	70	29.5	2.96
		1030	86	77	67	30.4	2.81
		1100	87	78	67	31.3	3.01
		1130	87	78	67	31.3	3.01
0817	2	1200	89	79	64	33.3	3.06
		1330	90	78	58	34.2	2.75
		1400	89	77	58	33.3	2.67
		1430	93	78	51	37.4	2.67
0819	1	0930	85	77	70	29.5	2.85
		1000	86	78	72	30.4	3.02
		1100	89	79	63	33.3	2.91
0819	2	1200	88	78	63	32.3	2.81
		1300	92	78	56	36.3	2.84
0823	1	0800	77	73	81	23.1	2.54
		0900	85	75	63	29.5	2.56
		1000	89	76	56	33.3	2.59
		1100	93	76	46	37.4	2.40
0823	2	1200	95	77	44	39.6	2.45
		1300	97	77	42	42.0	2.49
		1400	98	77	39	43.2	2.38
0825	1	0800	79	75	95	24.5	3.17
		0900	85	77	70	29.5	2.85
		1000	89	78	61	33.3	2.82
		1100	91	79	60	35.3	2.95
		1200	96	79	48	40.8	2.75
0825	2	1300	96	78	45	40.8	2.58
		1400	98	79	43	43.2	2.63
		1500	98	80	45	43.2	2.74
0901	1	0800	73	70	90	20.3	2.46
		0900	76	71	81	22.3	2.45
		1000	81	74	76	26.1	2.71
		1100	83	75	69	27.8	2.64
0901	2	1200	85	75	64	29.5	2.60
		1300	92	78	56	36.3	2.86
		1400	89	76	56	33.3	2.59
0906	1	0930	78	74	80	23.8	2.59
		1000	78	74	80	23.8	2.59
		1100	80	75	80	25.3	2.76
0906	2	1200	82	75	75	26.9	2.76
		1300	84	76	70	28.6	2.75
		1400	88	77	60	32.3	2.69
0908	1	0800	73	71	90	20.3	2.46
		0900	80	73	72	25.3	2.49
		1000	83	72	60	27.8	2.29
		1100	87	73	51	31.3	2.20
		1200	90	75	50	34.2	2.38
0908	2	1300	92	75	47	36.3	2.38
		1400	93	75	44	37.4	2.30
		1500	95	75	40	39.6	2.23
0913	1	0800	71	68	88	19.1	2.25
		0900	74	69	78	21.0	2.21
		1000	76	68	68	22.3	2.05
		1100	80	69	58	25.3	2.00
0913	2	1230	84	70	49	28.6	1.93
		1300	82	68	50	26.9	1.84
0922	1	0800	43	42	92	7.3	0.86
		0900	50	50	100	9.4	1.21
		1000	64	52	44	15.2	0.88
		1100	66	53	42	16.2	0.90
		1200	70	59	52	18.5	1.29
0922	2	1300	73	56	35	20.3	0.96
		1400	73	56	35	20.3	0.96
0926	1	0800	61	59	90	13.7	1.63
		0900	65	61	80	15.7	1.67
		1000	73	64	63	20.3	1.73
		1100	77	65	53	23.1	1.67
0926	2	1200	81	67	50	26.1	1.78

Table 15 lists the raw measurements and the derived flowrates.

The moisture in each of the gas samples was collected over an elapsed time of Δt minutes, and weighed (yielding M_i grams of collected water). The gas sample flowrate was constant for all cases at 2 dry standard liters per minute (0.070627 dry SCFM). The moisture concentration in the process gas gas streams, C_i^M, was therefore:

$$C_i^M = \frac{M_i \text{ grams} \times \frac{1}{453.6}\frac{\text{lbs}}{\text{gram}} \times \frac{1}{18.016}\frac{\text{lb moles}}{\text{lbs}}}{0.070627\ \frac{\text{DSCF}}{\text{min}} \times \Delta t\text{, min}}$$

$$C_i^M,\ \frac{\text{lb moles water}}{\text{Dry SCF}} = 1.7326 \times 10^{-3}\ \frac{M_i}{\Delta t}$$

Table 16 lists the raw and reduced data for moisture content. The subscript i refers to the same sampling points (K, AB, stack) as in the calculation of total dry gas flowrate.

Feed Rates of Liquids to the Kiln

Organic liquids were fed to the rotary kiln incinerator at predetermined volumetric flowrates, controlled with a positive displacement pump. The liquids were of four types: pure toluene, pure 1,2,4 trichlorobenzene (TCB), mixtures of TCB in toluene, or mixtures of hexachlorobenzene (HCB) in toluene. The mixture of either chlorinated benzene in toluene was made up by adding a known mass of either TCB or HCB to toluene and then adding sufficient toluene to bring the total mixture volume V_T to one gallon (3,785.3 ml).

The gravimetric composition of the mixtures was approximated by assuming additive volumes of the components. In general,

$$V_T = 3{,}785.3\ \frac{\text{ml}}{\text{gal}} \quad \frac{W_{TOL}}{\rho_{TOL}} + \frac{W_{TCB}}{\rho_{TCB}} + \frac{W_{HCB}}{\rho_{HCB}}$$

where W_{TOL}, W_{TCB}, and W_{HCB} are in grams per gallon, and where the specific gravities are(4):

TABLE 15. TOTAL FLOWRATES BY HELIUM TRACER METHOD

Test Date	Z_{STD} mm	Run	Clock Time	Z_K mm	Q_K SCFM	Clock Time	Z_{AB} mm	Q_{AB} SCFM	Clock Time	Z_s mm	Q_s SCFM
0817	100.25	1	0947	118.5	269	0952	52	613	0959	49.5	644
			0959	118.5	269	1014	52	613	1018	51	625
			1023	116	275	1027	52	613	1039	54	590
			1043	131	243	1050	54	590	1058	48	664
			1103	118	270	1108	50.5	631			
		2	1158	109	292	1203	60.5	527	1207	59.5	536
			1213	110	290	1217	61	522	1223	57	559
			1229	111	287	1234	60.5	527	1239	58	549
			1239	108	295	1259	64.5	494	1301	58.5	545
			1309	109	292	1315	61	522	1320	58	549
						1324	61.5	518			
0819	94.64	1	1039	159	189	1045	65	463	1106	62	485
						1100	66	456	1120	62	485
						1112	69	436			
		2	1125	177	170	1136	66	456	1146	59	510
			1155	174	173	1142	68	442			
						1151	65	463			
0823	100.25	1	1006	136	234	1011	67.5	472	1015	63	506
			1024	129	274	1029	67	476	1033	63	506
			1045	124	257	1050	66	483	1055	61	522
			1101	119	268	1105	67	476	1111	60.5	527
						1114	60	531			
		2	1210	174.5	183	1123	55	579	1119	55.5	574
			1245	165	193	1216	65	490	1128	57	559
						1230	64	498	1220	60	531
						1241	64	498	1224	61	522
						1250	64	498	1237	59	540
0825	95.38	1	1110	123	247	1116	49.5	612	1120	45.5	666
			1137	103	294	1141	48.5	625	1146	48.5	625
			1203	113	268	1207	51	594			
		2	1217	117	259	1222	50	606	1212	50.5	600
			1233	116.5	260	1238	50	606	1227	49	619
0901	98.25	1	1100	95	329	1105	54	578	1110	51	612
			1115	104.5	299	1120	53	589	1124	53	589
			1134	110	284	1138	52	601			
		2	1147	121	258	1152	61	512	1143	60	521
			1201	110	284	1206	60	521	1157	60.5	516
						1216	62	504	1210	59.5	525
									1221	59.5	525

TABLE 15. TOTAL FLOWRATES BY HELIUM TRACER METHOD (Con't)

Test Date	ZSTD mm	Run	Clock Time	ZK mm	QK SCFM	Clock Time	ZAB mm	QAB SCFM	Clock Time	Zs mm	Qs SCFM
0906	96.0	1	1117	124	246	1123	54	565	1128	51	598
			1133	121	252	1137	53.5	570	1142	51	598
			1146	126	242						
		2				1150	56	545	1155	44.5	686
						1205	50	610	1210	46	663
						1216	49	623	1238	49	623
						1233	54.5	560			
0908	100.76	1	1115	107	299	1120	50	641	1125	53	604
			1130	123.5	259	1135	53	604	1140	51	628
			1144	124	258	1148	54	593	1153	50	641
			1157	114.5	280	1201	54	593	1205	50	641
						1214	56	572			
		2				1236	57	562	1219	53	604
									1240	53	604
0913	96.38	1							1143	46	666
									1147	48	638
									1152	46	666
									1156	48	638
									1200	44	696
									1205	43	712
									1209	43	712
									1213	45	681
									1217	46	666
		2							1229	48	638
									1223	49	625
									1241	48	638
									1245	48	638
									1250	48	638
									1254	47	652
									1258	47.5	645
									1303	48	638
0922	103.88	1	1126	97	340	1132	44	750	1137	44	750
			1148	95	348	1154	45	734	1159	44	750
			1210	96	344	1214	45	734	1219	44.5	742
		2				1235	50	660	1240	47.5	695
						1245	50.5	654	1250	48	688

TABLE 15. TOTAL FLOWRATES BY HELIUM TRACER METHOD (Con't)

Test Date	Z_{STD} mm	Run	Clock Time	ZK mm	Q_K SCFM	Clock Time	Z_{AB} mm	Q_{AB} SCFM	Clock Time	Z_s mm	Q_s SCFM
0926	103.0	1	1021	92	356	1028	43	761	1034	44	744
			1041	96.5	339	1047	45.5	720	1051	45.5	720
			1107	93	352	1103	44.5	736	1056	47.5	689
			1122	92	356	1112	45	728	1117	45	728
						1128	44.5	736	1132	45	728
						1138	45.5	720			
		2	1301	97.5	336	1308	47	697	1313	47	697
			1319	116.5	281	1323	49.5	661	1328	51	642
			1333	108	303	1338	50	655			

TABLE 16. MOISTURE IN GAS STREAMS

Test Date	Run	Sample Start	Sample Stop	Δt, Min	Grams Water Collected			10^3 x lb Moles/Dry SCF		
					M_K	M_{AB}	M_s	C_K^M	C_{AB}^M	C_S^M
0817	1	0930	1110	100	16.5	17.6	129.4	0.286	0.305	2.242
0817	2	1145	1325	100	10.9	14.8	131.3	0.189	0.256	2.275
0819	1,2	—	—	100	11.2	14.0	104.0	0.194	0.243	1.802
0823	1	0950	1130	100	7.7	13.9	97.1	0.133	0.241	1.682
0823	2	1200	1250	50	7.5	7.2	42.9	0.260	0.249	1.487
0825	1,2	—	—	-	—	—	—	—	—	—
0901	1,2	1045	1225	100	10.9	12.8	39.2	0.189	0.222	0.679
0906	1,2	1100	1241	101	12.5	13.3	124.7	0.214	0.228	2.139
0908	1,2	1100	1240	100	13.1	13.6	111.1	0.226	0.236	1.925
0913	1,2	1125	1305	100	9.8	10.6	283.0	0.170	0.184	4.903
0922	1,2	—	—	-	—	—	—	—	—	—
0926	1,2	—	—	-	—	—	—	—	—	—

ρ_{TOL} = 0.8669 g/cc @ 20°C
ρ_{TCB} = 1.4542 g/cc @ 20°C
ρ_{HCB} = 1.5691 g/cc @ 23.6°C

Solving for the unknown W_{TOL},

$$W_{TOL} = \rho_{TOL}\left(3,785.3 - \frac{W_{TCB}}{\rho_{TCB}} - \frac{W_{HCB}}{\rho_{HCB}}\right)$$

Table 17 lists the calculated gravimetric compositions for each of the feed liquids used. At the actual volumetric feed rate in gallons per hour, the gravimetric feed rate for each component was calculated and is also listed in Table 17.

Continuous Measurements

Table 18 lists 20 measurements pertinent to the data reduction and analysis of process streamflows in the unquenched portion of the rotary kiln incineration system. These measurements are fundamentally continuous in nature, differing from those discussed in previous sections which are based upon either time-integrated sampling or analysis at discrete times.

During the testing time period covered by this status report, some evolution occurred in the data acquisition format for continuous measurements, as is shown by the notations in Table 18. Fourteen measurements were read and recorded manually from visual indicators or meters, at 15-minute or at 30-minute intervals, at the beginning of the test series.

Four of these measurements (P21, T49, F68, and F69) continued to be manually recorded throughout the test series. P21 is the static pressure at the feed end of the rotary kiln combustor, read from a meter in the control room in inches of water vacuum. T49 is the temperature of the gases in the exhaust duct from the afterburner. For the first testing on 0817, this measurement was recorded in degrees Centigrade; the measurement was recorded in degrees Fahreheit on subsequent testing dates. F68 and F69 are manually-recorded velocity heads, in inches of water, read from visual meters in the control room, for the pitot tubes in the inlet combustion air ducts to the kiln burner and the afterburner burner (respectively).

TABLE 17. LIQUIDS FED TO THE KILN

Test Date	Run	Feed Start Time	Feed Stop Time	Volumetric Feed Rate gph	Feed Liquid Composition Grams Per Gallon				Mass Feed Rate, g/hr			
					TCB	HCB	Toluene	Total	TCB	HCB	Toluene	Total
0817	1	—	—	0	0	0	0	0	0	0	0	0
0817	2	1130	1415	0.750	0	0	3,278	0	0	0	2,459	2,459
0819	1,2	0940	1237	0.750	0	133	3,204	3,338	0	100	2,403	2,503
0823	1,2	0945	1245	0.750	0	0	3,278	3,278	0	0	2,459	2,459
0825	1,2	1030	1350	0.750	0	0	3,278	3,278	0	0	2,459	2,459
0901	1	1034	1134	1.875	133	0	3,199	3,332	250	0	5,998	6,248
0901	2	1134	1315	0.750	133	0	3,199	3,332	100	0	2,399	2,499
0906	1,2	1026	1325	0.750	667	0	2,881	3,548	500	0	2,161	2,661
0908	1,2	1045	1410	0.750	1,333	0	2,484	3,817	1,000	0	1,863	2,863
0913	1,2	1015	1330	0.750	5,505	0	0	5,505	4,128	0	0	4,128
0922	1,2	—	—	0	0	0	0	0	0	0	0	0
0926	1,2	—	—	0	0	0	0	0	0	0	0	0

TABLE 18. DATA ACQUISITION FORMAT, CONTINUOUS MEASUREMENTS

I.D. Table 2	Measurement	Test Date									
		0817	0819	0823	0825	0901	0906	0908	0913	0922	0926
P21	Pressure, Kiln Combustion Gas	M	M	M	M	M	M	M	M	M	M
T53	Temperature, Propane Feed to Kiln	M	M	M	3	3	3	3	3	3	3
T54	Temperature, Propane Feed to Afterburner	M	M	M	4	4	4	4	4	4	4
T45	Temperature, Combustion Air to Kiln	NR	NR	NR	9	9	9	9	9	9	9
T46	Temperature, Combustion Air to Afterburner	NR	NR	NR	10	10	10	10	10	10	10
T50	Temperature, Kiln Combustion Gas	M	M	M	M	M	M	M	27	27	27
T51	Temperature, Afterburner Combustion Gas	M	M	M	23	23	24	24	23	23	23
T49	Temperature, Afterburner Exhaust Duct Gas	M	M	M	M	M	M	M	M	M	M
T43	Temperature, Kiln Backface Skin	M	M	M	2	2	2	2	2	2	2
T44	Temperature, Afterburner Skin (Side)	M	M	M	1	1	1	1	1	1	1
T55	Temperature, Afterburner Skin (Top)	NR	NR	NR	NR	NR	26	26	26	26	26
T47	Temperature, Venturi Entrance Skin	M	M	M	24	24	25	25	25	25	25
T48	Temperature, Venturi Exit Skin	M	M	M	25	25	23	23	24	24	24
F72	Flowrate, Propane Feed to Kiln	M	M	M	M	M	M	M	SC	SC	SC
F73	Flowrate, Propane Feed to Afterburner	M	M	M	M	M	M	M	SC	SC	SC
F68	Flowrate, Combustion Air to Kiln	M	M	M	M	M	M	M	M	M	M
F69	Flowrate, Combustion Air to Afterburner	M	M	M	M	M	M	M	M	M	M
-	Concentration, O_2 in Stack Gas	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
-	Concentration, CO_2 in Stack Gas	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC
-	Concentration, CO in Stack Gas	SC	SC	SC	SC	SC	SC	SC	SC	SC	SC

LEGEND: M - Manual Recording on Log Sheet from Visual Indicator
SC - Strip Chart Analog Record
NR - No Record Made
Numerical Entries - Channel I.D. on Multipoint Digital Temperature Recorder

Eight other of these measurements (T53, T54, T50, T51, T43, T44, T47, and T48) were manually recorded temperatures in earlier testing, but which were recorded on a multipoint digital recorder later in the test series (as indicated in Table 18).

Two additional measurements, F72 and F73, were initally manually-recorded milliampere readings from visual meters, of the output signal from the propane flowmeters. For the last three test dates, these milliampere signals were recorded on a single 10-inch analog strip chart (0-10 milliamps) running at approximately 10 cm/hr. The two measurements, recorded in different-colored inks, were also staggered in recording time on the chart.

Two temperatures, T45 and T46, were not recorded at all for the first three testing days. Data for T45 and T46, listed in Table 18, were actually time-interpolated values of the dry-bulb ambient air temperatures for 0817, 0819, and 0823. For later testing days, T45 and T46 were recorded on the digital multipoint recorder. One additional temperature, T55, was not recorded for early testing.

Three individual 10-cm analog strip charts, with a chart speed of approximately 3 cm/hr, recorded the stack gas concentrations (dry basis) of oxygen (0-25 per cent), carbon dioxide (0-10 per cent), and carbon monoxide (0-100 ppm).

Table 19 lists the data taken at discrete times with 15-minute or 30-minute intervals, for the continuous measurements. Only data during the selected steady-state portions of tests are listed in Table 19, although data at other test times exists in original format.

Difficulties were encountered in generating a time-consistent set of raw test data for Table 19, attributable to the diversity of primary data sources which were not mutually synchronized. For example, the discrete times selected for reading and manually recording data from visual indicators did not consistently correspond to the discrete times selected for printing on the multipoint digital temperature recorder. Another example is the absence of precise timing marks on the four analog strip chart records, which have imprecise and independent chart speeds.

TABLE 19. RAW AND REDUCED DATA AT DISCRETE TIMES FOR CONTINUOUS MEASUREMENTS

Test Date	Run	Clock Time	Kiln Pressure, in H_2O	Propane Flowmeters, Ma		Propane Temp., °F		Propane Flowrate, SCFM		Combust. Air Vel Head, in H_2O		Combust. Air Temp., °F		Combust. Air Flowrate, SCFM		Stack O_2 %	Stack CO_2 %	Stack CO ppm	Intern Temps, °F			External Temps, °F				
				Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB				Ki[illegible]		AB Exit	Kiln	AB Side	AB Top	U-Bend Entrance	U-Bend Exit
			P21	F72	F73	T53	T54	P_k	P_{AB}	F68	F69	T45	T46	A_{KB}	A_{AB}	X_{O_2}	X_{CO_2}	X_{CO}		[illegible]51	T49	T43	T44	T55	T47	T48
0817	1	0945	0.04	8.5	9.0	105	101	8.62	9.65	0.44	0.84	(85)	(85)	275	349	9.3	7.8	0	1400	1987	1810	290	186			
		1000	0.055	8.25	8.9	104	109	8.16	9.32	0.46	0.83	(85)	(85)	280	346	9.8	7.5	0	1400	1985	1810	303	194		432	369
		1015	0.04	8.5	9.0	107	112	8.59	9.46	0.39	0.82	(86)	(86)	258	344	9.8	7.4	0	1405	1978	1810	314	203			
		1030	0.04	8.25	8.9	109	115	8.08	9.22	0.44	0.83	(86)	(86)	273	346	10.0	7.3	0	1405	1971	1810	325	222		433	374
		1045	0.035	8.1	8.9	112	110	7.76	9.18	0.36	0.83	(86)	(86)	240	346	9.8	7.4	0	1405	1965	1810	331	239			
		1100	0.030	8.0	8.6	113	120	7.56	8.58	0.38	0.84	(87)	(87)	254	347	10.0	7.3	0	1405	1962	1810	339	251		435	363
		1115	0.045	8.0	8.6	116	123	7.52	8.54	0.34	0.83	(87)	(87)	240	345	10.0	7.2	0	1405	1971	1810	347	265			
		1130	0.05	7.9	8.8	116	124	7.33	8.90	0.40	0.82	(87)	(87)	261	344	10.3	7.1	0	1405	1971	1810	351	273		435	369
0817	2	1145	0.045	6.75	8.6	118	129	5.15	8.45	0.21	0.83	(88)	(88)	188	345	10.5	7.1	0	1405	1976	1810	358	281			
		1200	0.04	6.9	8.6	120	131	5.41	8.42	0.19	0.84	(89)	(89)	179	347	10.5	7.1	0	1410	1969	1810	358	288		432	367
		1215	0.055	6.6	8.6	122	132	4.84	8.41	0.20	0.82	(89)	(89)	184	343	10.3	7.1	0	1410	1965	1810	361	292			
		1230	0.04	6.75	8.6	122	134	5.11	8.38	0.21	0.83	(89)	(89)	188	345	10.3	7.1	0	1410	1967	1810	365	294		428	367
		1245	0.05	6.75	8.6	124	136	5.10	8.35	0.21	0.82	(89)	(89)	188	343	10.5	7.1	0	1410	1962	1810	366	301			
		1300	0.05	6.9	8.6	125	136	5.37	8.35	0.18	0.82	(89)	(89)	174	343	10.5	7.0	0	1410	1960	1810	367	307		430	363
		1315	0.04	6.6	8.6	125	138	4.81	8.33	0.19	0.84	(89)	(89)	179	347	10.5	7.0	0	1410	1965	1810	370	312			
		1330	0.05	6.75	8.75	126	138	5.08	8.60	0.20	0.83	(90)	(90)	184	345	10.5	7.0	0	1410	1965	1810	371	313		430	367
		1345	0.05	6.6	8.6	127	139	4.79	8.31	0.19	0.80	(89)	(89)	179	338	10.5	7.0	0	1410	1974	1810	373	316			
		1400	0.04	6.9	8.75	127	140	5.35	8.57	0.18	0.83	(89)	(89)	174	345	10.5	7.0	0	1410	1965	1810	373	318		433	365
		1415	0.04	6.75	9.1	127	139	5.07	9.21	0.20	0.84	(91)	(91)	183	346	10.5	7.0	0	1410	1967	1810	371	320			
0819	1	0945	0.04	5.9	8.6	97	93	3.69	9.00	0.14	0.84	(86)	(86)	154	348	10.5	7.2	0	1220	1819	1600	223	135			
		1000	0.04	5.9	8.4	101	96	3.67	8.57	0.13	0.81	(86)	(86)	149	342	10.8	7.0	0	1280	1797	1610	235	150		377	332
		1015	0.035	5.9	8.1	104	99	3.65	7.94	0.14	0.78	(87)	(87)	154	325	11.0	6.8	0	1310	1788	1610	247	167			
		1030	0.035	5.9	8.1	110	101	3.61	7.91	0.14	0.80	(88)	(88)	154	339	11.0	6.6	0	1300	1791	1610	257	186		384	339
		1045	0.04	5.8	8.1	112	104	3.41	7.87	0.14	0.79	(89)	(89)	154	336	11.8	6.7	0	1325	1778	1610	266	198			
		1100	0.04	5.8	8.1	113	105	3.40	7.85	0.12	0.76	(89)	(89)	143	330	11.3	6.5	0	1340	1765	1610	270	212		384	339
		1115	0.045	5.9	8.1	115	107	3.58	7.83	0.14	0.78	(89)	(89)	154	334	11.3	6.5	0	1350	1765	1610	279	225			
0819	2	1130	0.05	5.9	8.0	118	109	3.56	7.61	0.14	0.73	(89)	(89)	154	323	11.5	6.5	0	1400	1765	1610	285	235		390	342
		1145	0.045	6.0	8.0	122	111	3.72	7.58	0.14	0.73	(89)	(89)	154	323	11.5	6.4	0	1425	1760	1610	290	243			
		1200	0.035	6.0	7.9	120	111	3.73	7.39	0.13	0.70	(88)	(88)	149	317	11.3	6.6	0	1425	1767	1610	294	251		386	338
		1215	0.045	6.0	7.85	123	113	3.71	7.27	0.14	0.70	(89)	(89)	154	317	11.3	6.5	0	1450	1769	1610	300	258			
		1230	0.035	6.0	7.9	124	113	3.71	7.37	0.13	0.72	(90)	(90)	148	321	11.3	6.4	0	1400	1763	1610	303	264		384	338
0823	1	0945	0.04	5.9	8.5	98	94	3.69	8.79	0.14	0.82	(88)	(88)	154	343	10.5	7.3	0	1190	1828	1610	211	125			
		1000	0.04	5.9	8.5	102	97	3.66	8.74	0.14	0.82	(89)	(89)	154	343	10.8	7.1	0	1210	1800	1610	221	146		365	325
		1015	0.04	5.9	8.4	105	100	3.64	8.50	0.14	0.83	(90)	(90)	154	345	11.0	7.0	0	1240	1806	1610	234	160			
		1030	0.04	5.9	8.45	109	103	3.61	8.55	0.14	0.82	(91)	(91)	154	342	11.0	6.8	0	1260	1790	1614	245	176		368	329
		1045	0.04	5.9	8.25	113	105	3.59	8.14	0.14	0.78	(92)	(92)	154	333	11.3	6.7	0	1265	1781	1610	255	190			
		1100	0.05	6.0	8.25	115	108	3.76	8.10	0.14	0.76	(93)	(93)	154	329	11.3	6.7	0	1265	1784	1610	264	199		360	330
	2	1115	0.045	5.9	8.2	117	110	3.56	7.97	0.14	0.78	(93)	(93)	154	333	11.5	6.6	0	1300	1778	1610	273	214			
		1130	0.05	6.0	8.2	120	111	3.73	7.96	0.14	0.74	(94)	(94)	153	324	11.3	6.5	0	1300	1774	1610	279	226		363	329
		1145	0.05	6.0	8.2	121	113	3.73	7.93	0.14	0.75	(94)	(94)	153	326	11.5	6.6	0	1320	1781	1620	285	234			
		1200	0.045	6.0	8.25	124	115	3.71	8.00	0.13	0.74	(95)	(95)	148	324	11.5	6.5	0	1325	1778	1620	293	246		374	328
		1215	0.055	6.0	8.1	127	117	3.69	7.69	0.14	0.72	(95)	(95)	153	319	11.8	6.4	0	1330	1765	1620	299	256			
		1230	0.05	6.0	8.1	129	119	3.68	7.66	0.13	0.72	(96)	(96)	148	319	11.8	6.3	0	1335	1765	1625	303	262		374	330
		1245	0.06	6.1	8.1	129	120	3.86	7.65	0.14	0.73	(96)	(96)	153	321	11.5	6.3	5	1350	1767	1625	308	268			

TABLE 19. RAW AND REDUCED DATA AT DISCRETE TIMES FOR CONTINUOUS MEASUREMENTS (Con't)

Test Date	Run	Clock Time	Kiln Pressure, in H_2O	Propane Flowmeters, Ma		Propane Temp., °F		Propane Flowrate, SCFM		Combust. Air Vel Head, in H_2O		Combust. Air Temp., °F		Combust. Air Flowrate, SCFM		Stack O_2 %	Stack CO_2 %	Stack CO ppm	Intern Temps, °F			External Temps, °F				
				Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB				Kiln	AB	AB Exit	Kiln	AB Side	AB Top	U-Bend Entrance	U-Bend Exit
			P21	F72	F73	T53	T54	P_k	P_{AB}	F68	F69	T45	T46	A_{KB}	A_{AB}	X_{O_2}	X_{CO_2}	X_{CO}	T50	T51	T49	T43	T44	T55	T47	T48
0825	1	1030	0.04	9.9	9.8	112	108	11.16	11.05	0.74	0.82	110	97	348	340	6.3	8.2	0	1500	2108	1940	331	200		429	373
		1045	0.04	10.0	9.8	116	111	11.27	10.99	0.80	0.84	113	100	360	344	6.5	8.5	0	1575	2143	1960	350	218		444	384
		1100	0.035	9.4	9.8	120	124	10.08	10.75	0.80	0.83	116	105	360	340	6.5	8.4	0	1590	2158	1980	363	235		449	384
		1115	0.06	9.75	9.8	124	130	10.66	10.64	0.61	0.82	119	108	313	337	6.8	8.4	0	1590	2167	2000	375	252		451	393
		1130	0.05	9.5	9.9	127	132	10.14	10.79	0.68	0.82	121	111	330	336	6.8	8.2	0	1600	2167	2000	382	266		454	388
		1145	0.065	9.2	9.75	130	135	9.54	10.46	0.56	0.83	124	116	299	337	7.0	8.1	0	1600	2179	2000	390	275		453	391
		1200	0.04	8.9	9.8	133	132	8.94	10.60	0.49	0.82	126	119	279	334	7.0	8.2	0	1600	2168	2000	397	284		453	390
0825	2	1215	0.03	8.75	9.6	135	137	8.64	10.15	0.52	0.82	128	123	287	333	7.3	8.0	0	1600	2157	2000	403	294		449	389
		1230	0.06	8.65	9.75	138	135	8.42	10.46	0.44	0.82	130	127	263	332	7.5	7.9	0	1600	2157	2000	409	304		451	398
		1245	0.04	8.6	9.75	139	128	8.31	10.58	0.48	0.84	131	129	275	335	7.5	7.9	0	1600	2165	2000	412	316		458	394
		1300	0.08	9.1	9.8	141	128	9.18	10.68	0.50	0.82	132	130	280	331	7.3	7.8	0	1600	2158	2000	415	325		459	395
		1315	0.035	8.45	9.6	144	132	7.97	10.24	0.38	0.81	134	135	244	327	7.3	7.9	0	1600	2170	2000	418	326		452	393
		1330	0.03	8.6	9.65	145	131	8.23	10.35	0.34	0.81	135	138	231	326	7.5	7.8	0	1600	2160	2000	419	334		458	396
		1345	0.05	8.5	9.6	146	130	8.04	10.27	0.40	0.83	136	140	250	330	7.5	7.8	10	1600	2164	2000	423	349		457	396
0901	1	1045	0.09	8.25	9.6	105	101	8.14	10.80	0.30	0.82	85	87	226	343	7.3	8.2	0	1600	2083	1920					
		1100	0.04	7.5	9.6	109	103	6.66	10.77	0.24	0.81	83	89	203	341	7.3	8.3	0	1600	2109	1940	327	196		407	366
		1115	0.035	7.5	9.6	113	105	6.61	10.73	0.30	0.80	86	90	226	338	10.3	8.1	0	1600	2128	1960					
		1130	0.035	7.5	9.8	116	107	6.58	11.07	0.28	0.82	85	91	219	342	10.3	6.5	0	1600	2141	1975	349	235		419	366
0901	2	1145	0.04	6.5	9.6	120	109	4.67	10.65	0.20	0.80	88	92	184	338	11.5	5.6	0	1600	2156	1980					
		1200	0.03	6.75	9.75	123	111	5.11	10.90	0.18	0.81	89	92	175	340	14.3	4.1	0	1600	2165	2000	362	263		426	383
		1215	0.03	6.5	9.5	126	113	4.62	11.14	0.19	0.79	90	96	179	334	15.0	3.8	0	1600	2174	2000					
0906	1	1030	0.045	9.75	9.6	102	100	11.07	10.82	0.70	0.82	85	87	346	343	6.5	8.3	0	1555	2053	1910	320	189	212	478	376
		1045	0.045	8.75	9.6	107	102	9.07	10.78	0.46	0.82	86	88	280	343	6.8	8.3	0	1590	2106	1940					
		1100	0.03	8.25	9.6	111	105	8.06	10.73	0.50	0.86	88	88	291	351	6.8	8.1	0	1600	2121	1950	346	220	250	491	385
		1115	0.045	8.1	9.6	114	107	7.73	10.69	0.40	0.82	87	89	261	343	6.5	8.3	0	1600	2157	1975					
		1130	0.025	7.8	9.75	117	109	7.13	10.94	0.40	0.82	88	91	261	342	6.8	8.3	0	1600	2168	1990	364	250	276	499	387
		1145	0.035	8.25	9.75	120	112	7.93	10.88	0.36	0.82	91	91	247	342	7.0	8.2	0	1600	2160	2000					
0906	2	1200	0.04	8.0	9.75	123	114	7.43	10.84	0.32	0.84	91	95	232	345	7.0	8.1	0	1600	2163	2000	378	276	298	511	397
		1215	0.04	8.1	9.75	125	116	7.59	10.80	0.36	0.80	89	95	247	337	7.3	8.0	0	1600	2156	2000					
		1230	0.04	7.9	9.6	127	118	7.19	10.49	0.32	0.83	94	96	232	343	7.3	7.9	0	1600	2152	2000	385	299	318	516	402
		1245	0.05	8.0	9.6	129	119	7.35	10.47	0.34	0.82	94	96	239	341	7.0	8.1	0	1600	2163	2000					
		1300	0.035	7.5	9.4	131	120	6.41	10.08	0.28	0.80	94	94	217	337	7.3	8.0	0	1600	2154	2000	392	310	329	513	400
		1315	0.025	7.45	9.5	132	122	6.31	10.23	0.28	0.82	96	98	217	340	7.0	8.0	0	1600	2160	2000					
0908	1	1045	0.04	9.4	9.6	113	109	10.20	10.65	0.63	0.80	93	95	326	337	7.8	8.1	0	1590	2111	1960					
		1100	0.045	8.45	9.75	118	112	8.33	10.88	0.44	0.82	93	97	272	340	7.8	7.9	0	1600	2118	1960	360	238	263	500	392
		1115	0.06	8.6	9.9	121	114	8.57	11.12	0.42	0.81	93	98	266	338	7.3	7.9	0	1600	2146	1980					
		1130	0.02	7.6	9.9	125	116	6.66	11.09	0.39	0.80	97	99	255	336	7.5	8.2	0	1600	2166	2000	374	262	285	506	392
		1145	0.05	8.0	9.8	128	119	7.36	10.84	0.34	0.80	96	101	239	335	7.8	8.1	0	1600	2167	2000					
		1200	0.05	8.1	9.75	131	121	7.51	10.71	0.31	0.81	97	103	228	336	7.8	8.0	0	1600	2169	2000	385	286	308	515	403
		1215	0.03	7.9	9.6	133	123	7.12	10.40	0.28	0.82	98	100	216	339	7.8	8.1	0	1600	2158	2000					

TABLE 19. RAW AND REDUCED DATA AT DISCRETE TIMES FOR CONTINUOUS MEASUREMENTS (Con't)

Test Date	Run	Clock Time	Kiln Pressure, in H_2O	Propane Flowmeters, Mm		Propane Temp., °F		Propane Flowrate, SCFM		Combust. Air Vel Head, in H_2O		Combust. Air Temp., °F		Combust. Air Flowrate, SCFM		Stack O_2 %	Stack CO_2 %	Stack CO ppm	Intern Temps, °F			External Temps, °F				
				Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB	Kiln	AB				Kiln	AB	AB Exit	Kiln	AB Side	AB Top	U-Bend Entrance	U-Bend Exit
			P21	F72	F73	T53	T54	P_k	P_{AB}	F68	F69	T45	T46	A_{KB}	A_{AB}	X_{O_2}	X_{CO_2}	X_{CO}	T50	T51	T49	T43	T44	T55	T47	T48
0908	2	1230	0.035	7.5	9.5	131	125	6.41	10.18	0.29	0.81	97	102	220	337	7.8	8.0	0	1600	2157	2000	395	304	323	514	401
		1245	0.04	7.9	9.5	137	126	7.07	10.16	0.30	0.82	97	107	224	337	7.8	8.1	0	1600	2154	2000					
		1300	0.03	7.75	9.5	137	127	6.80	10.14	0.30	0.81	98	106	224	336	8.0	8.0	0	1600	2157	2000	395	316	330	508	393
		1315	0.05	7.75	9.5	140	129	6.76	10.11	0.28	0.82	100	106	216	338	7.8	7.9	0	1600	2151	2000					
		1330	0.04	7.75	9.5	142	130	6.74	10.09	0.31	0.81	101	101	227	337	8.0	7.9	1	1600	2150	2000	404	326	340	514	401
		1345	0.03	7.45	9.5	143	132	6.19	10.06	0.26	0.81	98	109	208	335	8.0	7.9	2	1600	2147	2000					
		1400	0.035	7.5	9.6	145	133	6.26	10.22	0.26	0.81	101	109	208	335	8.0	7.8	2	1600	2148	2000	409	337	348	517	403
0913	1	1030	0.04	9.65	9.45	98	95	10.96	10.63	0.62	0.84	82	85	326	348	7.5	8.3	0	1604	2047	1910					
		1045	0.03	9.62	9.45	102	98	10.82	10.57	0.62	0.84	81	85	327	348	7.3	8.2	0	1613	2075	1940	326	192	227	492	390
		1100	0.03	9.53	9.51	105	101	10.59	10.63	0.66	0.82	83	86	336	344	7.5	8.1	0	1610	2081	1950					
		1115	0.045	9.40	9.53	108	104	10.29	10.61	0.66	0.83	84	87	336	346	7.8	8.0	0	1619	2093	1960	351	223	253	489	393
		1130	0.03	9.22	9.56	111	106	9.89	10.63	0.61	0.84	85	88	323	347	-	-	0	1619	2114	1975					
		1145	0.05	9.39	9.60	114	108	10.16	10.67	0.58	0.84	85	92	315	346	-	-	0	1616	2120	1990	371	257	289	509	397
		1200	0.05	9.36	9.60	116	110	10.07	10.63	0.56	0.82	86	92	309	342	-	-	0	1614	2107	2000					
		1215	0.06	9.37	9.64	118	112	10.06	10.67	0.59	0.82	88	93	317	342	-	-	0	1622	2142	2000	382	278	305	508	403
0913	2	1230	0.03	9.06	9.53	121	113	9.43	10.45	0.51	0.82	90	92	294	342	-	-	0	1620	2133	2000					
		1245	0.045	9.00	9.53	122	115	9.30	10.41	0.49	0.82	89	93	288	342	-	-	0	1618	2147	2000	390	290	313	496	398
		1300	0.05	9.05	9.51	124	116	9.36	10.35	0.52	0.82	90	95	297	341	-	-	0	1618	2141	2000					
		1315	-	9.05	9.53	126	118	9.33	10.35	-	-	91	96	-	-	-	-	0	1618	2145	-	399	309	326	504	401
		1330	0.035	9.05	9.50	127	119	9.31	10.43	0.55	0.82	92	95	305	341	-	-	0	1617	2128	2000					
0922	1	1100	0.05	9.45	9.45	95	90	10.63	10.72	0.68	0.86	70	74	346	356	8.0	8.0	0	1600	2077	1930					
		1115	0.025	9.50	9.48	98	93	10.67	10.73	0.70	0.88	72	74	350	360	8.5	7.8	0	1607	2063	1950	338	221	252	492	388
		1130	0.04	9.36	9.55	100	95	10.36	10.73	0.73	0.86	71	76	358	355	8.5	7.7	0	1603	2078	1960					
		1145	0.04	9.31	9.55	102	96	10.23	10.69	0.61	0.86	73	76	326	355	8.5	7.7	0	1604	2085	1975	350	249	275	499	392
		1200	0.05	9.28	9.55	105	99	10.11	10.63	0.65	0.87	74	80	337	356	8.8	7.7	0	1600	2095	1980					
		1215	0.04	8.90	9.55	107	100	9.35	10.59	0.65	0.84	73	79	337	350	8.3	7.8	0	1615	2129	1990	362	265	289	494	388
0922	2	1230	0.03	8.83	9.48	109	102	9.19	10.55	0.58	0.86	73	81	318	354	8.5	7.7	0	1610	2140	1995					
		1245	0.03	8.83	9.46	112	104	9.14	10.48	0.56	0.86	77	84	312	353	8.5	7.7	0	1602	2134	2000	373	288	308	507	395
		1300	0.04	8.75	9.43	113	106	8.97	10.38	0.54	0.85	78	84	306	351	8.8	7.6	0	1616	2132	2000					
		1315	0.03	8.85	9.40	114	107	9.14	10.31	0.50	0.85	77	83	294	351	8.8	7.6	0	1612	2132	2000	377	297	313	499	390
		1330	0.035	8.90	9.41	116	108	9.21	10.31	0.54	0.85	78	83	306	351	8.8	7.6	0	1610	2137	2000					
		1345	0.045	8.85	9.41	118	109	9.08	10.29	0.54	0.86	78	86	306	352	8.8	7.5	0	1613	2133	2000	385	309	326	507	393
		1400	0.045	8.83	9.42	119	111	9.03	10.27	0.54	0.86	81	82	305	353	8.8	7.5	0	1611	2134	2000					
0926	1	1000	0.035	9.20	9.60	82	80	10.38	11.22	0.66	0.88	74	76	339	359	-	-	0	1197	1690	1600	174	143	157	364	193
		1015	0.04	9.22	8.56	85	83	10.37	9.09	0.64	0.89	76	76	333	361	10.3	6.7	0	1280	1649	1600					
		1030	0.025	9.25	8.21	88	87	10.37	8.33	0.70	0.83	76	79	349	348	10.8	6.6	0	1375	1675	1600	218	169	183	403	206
		1045	0.04	9.24	7.76	91	90	10.29	7.40	0.64	0.60	77	78	333	296	10.8	6.5	0	1377	1643	1610					
		1100	0.035	8.95	7.73	94	93	9.67	7.30	0.64	0.72	80	81	332	324	11.3	6.3	0	1375	1640	1600	258	193	212	415	217
		1115	0.045	9.39	7.59	97	96	10.47	6.99	0.67	0.68	80	83	340	314	11.0	6.4	0	1449	1642	1600					
		1130	0.04	9.41	7.41	99	99	10.47	6.60	0.68	0.63	82	85	342	302	11.3	6.3	0	1487	1645	1600	284	214	229	413	208
0926	2	1230	0.05	9.59	9.84	110	105	10.61	11.19	0.65	0.83	87	90	333	345	8.5	7.7	0	1602	2051	1940	342	250	268	481	245
		1245	0.04	9.60	9.88	112	107	10.60	11.22	0.64	0.86	86	90	330	351	8.3	7.9	0	1633	2068	1960					
		1300	0.03	9.62	9.93	114	109	10.60	11.28	0.64	0.84	88	91	330	346	8.3	7.9	0	1638	2082	1980	360	263	286	494	252

Reduction of Propane Flow Rate Data

The signal transmitted by each of the two laminar venturi propane flowmeters (measurements F72 and F73) is a milliamp output, linearly related to propane flowrate:

$$\text{Propane Flowrate, CFM} = 2.200\ (\text{ma} - 4).$$

Because the feed lines and flowmeters are in close proximity to the hot combustors, the temperature rise during a test is significant and progressive. A temperature correction is applied to determine flowrate in SCFM (referenced to 32°F):

$$P_K \text{ or } P_{AB} = 2.200\ (\text{ma} - 4) \left(\frac{459.7 + 32}{459.7 + \theta_P} \right)$$

where P_K = Propane Flowrate to Kiln, SCFM

P_{AB} = Propane Flowrate to Afterburner, SCFM

ma = Milliamp Signal from F72 (Kiln) or F73 (Afterburner) Flowmeters

θp = Temperature, °F, Measured by T53 (Kiln) or T54 (Afterburner)

Table 19 lists the calculated values for P_K and P_{AB}.

At the reference temperature of 32°F, and at a nominal pressure of one atmosphere, the volume occupied by one pound mole is 359.05 cubic feet. Hence,

$$\text{Pound Moles Per Minute Propane to Kiln or to Afterburner} = \frac{P_K \text{ or } P_{AB}}{359.05}.$$

A specification for the commercial propane utilized at the CRF was:

Isobutane	1.5 to 2.5 mole per cent
Normal Butane	0.02 to 0.03 mole per cent
Ethane	1.5 to 3.0 mole per cent
Propane	Balance

Reduction of Combustion Air Flowrate Data

The raw data measured for either the flowrate of combustion air to the kiln (F68) or to the afterburner (F69) is the velocity head (in inches of water) from a pitot tube in a 4-inch inlet duct to the blower. Calibrations were performed on November 29, 1983, with 60°F air, using the helium tracer method as a calibration standard. The results were:

$$A_{KB} = 434.96 \left(\frac{459.7 + 32}{459.7 + \theta_{AK}}\right)^{1/2} (p_K)^{1/2}$$

$$A_{AB} = 399.90 \left(\frac{459.7 + 32}{459.7 + \theta_{AA}}\right)^{1/2} (p_A)^{1/2}$$

where A_{KB} and A_{AB} are the combustion air flowrates, SCFM, to the kiln and afterburner (respectively)

θ_{AK} and θ_{AA} are the measured combustion air temperatures, T45 and T46, °F, to the kiln and afterburner (respectively)

p_K and p_A are the measured velocity heads, F68 and F69, inches of water, for the kiln and afterburner (respectively).

Table 19 lists the calculated values for A_{KB} and A_{AB}.

The standard pitot tube relationship of $V_o = C\sqrt{2g\Delta H}$ reduces, for air in a 4-inch duct, to:

$$A = 337.18\ C \left(\frac{459.7 + 32}{459.7 + \theta_A}\right)^{1/2} (p)^{1/2}$$

where C is a coefficient generally between 0.8 and 1.0(5). The values for C corresponding to the November 29th calibration are 1.290 (kiln) and 1.186 (afterburner). Values for C greater than unity could be explained by positioning of the pitot tube off the axis of the duct, or by skewed airflow due to bends and/or entrance effects in the duct (50 diameters of straight duct are recommended upstream of the pitot tube).

ANALYSIS OF PROCESS FLOWRATE DATA

Time Averages of Measured Quantities

Table 20 summarizes the time averages for 17 measured quantities, for each of the 20 runs. The time periods used for averaging were chosen using two conditions: (1) data averaging periods were always totally within the bounds of the corresponding periods for acquiring time-integrated samples for POHC analysis; and (2) the best available approximation of steady-state conditions led to rejection, in some runs, of early or late data points.

TABLE 20. TIME AVERAGES OF MEASURED QUANTITIES

		Test Date & Run	0817-1	0817-2	0819-1	0819-2	0823-1	0823-2	0825-1	0825-2	0901-1	0901-2	0906-1	0906-2	0908-1	0908-2	0913-1	0913-2	0922-1	0922-2	0926-1	0926-2
		Start Time	0945	1131	0945	1121	0945	1115	1030	1211	1034	1139	1026	1147	1045	1217	1030	1218	1100	1221	1000	1230
		Stop Time	1130	1415	1120	1230	1114	1245	1210	1350	1138	1215	1146	1325	1216	1410	1217	1330	1220	1400	1140	1300
Measured Quantities	W	Mol Percent H_2O in Air	2.926	2.790	2.928	2.824	2.522	2.438	2.909	2.646	2.566	2.683	2.646	2.733	2.364	2.302	2.131	1.885	1.028	0.958	1.673	1.779
	Q_K	Kiln Exh., Dry SCFM (He)	265.2	291.2	109.2	171.5	251.5	107.9	269.7	259.7	303.8	271.0	246.8	—	274.2	—	—	—	343.9	—	350.7	306.6
	Q_{AB}	AB Exh., Dry SCFM (He)	612.0	518.3	451.5	453.7	487.4	512.6	610.6	606.3	509.4	512.0	567.7	584.5	600.6	561.9	—	—	739.2	657.1	733.2	670.9
	Q_S	Stack Exh., Dry SCFM (He)	630.8	547.6	485.2	509.9	515.2	545.3	645.6	609.5	600.8	521.6	598.3	657.2	628.3	604.3	675.1	639.1	747.6	691.5	721.6	669.2
	P_K	Propane to Kiln, SCFM	7.953	5.090	3.573	3.606	3.658	3.709	10.256	8.399	6.998	4.800	8.498	7.047	7.964	6.604	10.335	9.346	10.225	9.109	10.289	10.603
	P_{AB}	Propane to AB, SCFM	9.106	8.489	8.136	7.444	8.470	7.837	10.754	10.308	10.843	10.897	10.807	10.485	10.813	10.137	10.630	10.398	10.682	10.370	8.133	11.230
	A_{KB}	Kiln Burner Air, SCFM	261.1	181.8	151.7	151.8	154.0	151.7	327.0	261.4	218.5	179.3	281.0	230.7	257.4	218.1	323.6	296.0	342.3	306.7	338.3	331.0
	A_{AB}	AB Burner Air, SCFM	345.9	344.3	337.7	320.2	339.2	323.7	338.3	330.6	341.0	337.3	344.0	340.5	337.3	336.4	345.4	341.5	355.3	352.1	329.1	347.3
	TOL	Toluene Feed, g/h	0	2459	2403	2403	2459	2459	2459	2459	5998	2399	2161	2161	1863	1863	0	0	0	0	0	0
	HCB	Hexachlorobenzene, g/h	0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TCB	Trichlorobenzene, g/h	0	0	0	0	0	0	0	0	250	100	500	500	1000	1000	4128	4128	0	0	0	0
	X_{O_2}	Stack O_2, Dry mol %	9.88	10.46	11.10	11.38	10.98	11.56	6.70	7.41	8.80	14.94	6.73	7.15	7.69	7.91	8.15	—	8.43	8.71	10.91	8.38
	X_{CO_2}	Stack CO_2, Dry mol %	7.38	7.05	6.76	6.48	6.93	6.46	8.29	7.87	7.78	3.57	8.25	8.02	8.04	7.94	7.53	—	7.78	7.60	6.47	7.80
	Θ_K	Kiln Temp, °F	1404	1410	1304	1420	1238	1323	1579	1600	1600	1599	1591	1600	1599	1600	1615	1618	1605	1611	1363	1621
	Θ_{AB}	AB Temp, °F	1974	1967	1786	1765	1798	1773	2156	2162	2115	2162	2128	2158	2148	2152	2097	2139	2088	2135	1655	2088
	Θ_X	AB Exhaust Temp, °F	1810	1810	1609	1610	1611	1619	1983	2000	1949	1997	1961	2000	1986	2000	1966	2000	1964	1999	1600	1974
	V_K	Kiln Vac., in H_2O	0.042	0.045	0.039	0.042	0.042	0.051	0.047	0.046	0.050	0.034	0.038	0.038	0.042	0.037	0.042	0.040	0.041	0.036	0.037	0.045
Calculated Parameters	Q_{KC}	Calc Kiln Exh., Dry SCFM	294.4	200.6	140.0	157.4	173.7	212.5	303.6	305.1	278.8	205.5	254.4	274.3	292.9	253.5	—	—	408.9	329.1	425.9	352.2
	Q_K/Q_{KC}	Kiln Exh Ratio, Meas/Calc	0.901	1.452	1.352	1.089	1.448	0.884	0.888	0.851	1.090	1.318	0.970	—	0.936	—	—	—	0.841	—	0.823	0.870
	A_{KT}	Total Kiln Air, SCFM	319.7	217.6	152.3	170.2	186.4	226.1	334.5	331.4	302.2	221.7	279.3	297.0	316.6	273.3	—	—	433.8	350.7	454.1	380.2
	A_{KL}	$A_{KT} - A_{KB}$, SCFM	58.6	35.8	0.6	18.4	34.2	74.4	7.5	70.0	83.7	42.4	-1.7	66.3	59.2	55.2	—	—	91.5	44.0	115.8	49.2
	OK_F	O_2/SX Propane in K Burner	1.338	1.455	1.730	1.680	1.723	1.675	1.300	1.272	1.277	1.526	1.351	1.337	1.325	1.354	1.284	1.304	1.391	1.400	1.357	1.287
	OF_{AB}	O_2/SX Propane in AB Burner	1.548	1.655	1.691	1.755	1.639	1.692	1.282	1.311	1.286	1.264	1.301	1.326	1.279	1.361	1.335	1.353	1.382	1.411	1.670	1.275

The 17 averages of measured quantities in Table 20 included four (W, Q_K, Q_{AB}, and Q_S, with original reduced data in Tables 14 and 15) based upon periodic measurements; three (TOL, TCB, and HCB feed rates, with original data in Table 17) based upon predetermined liquid feed composition and feed rate assumed constant with time; and ten (P_K, P_{AB}, A_{KB}, A_{AB}, X_{O_2}, X_{CO_2}, θ_K, θ_{AB}, θ_X, and V_K) based upon the raw and reduced data, in Table 19 at discrete times, for continuous measurements. An additional parameter from Table 19, the stack gas carbon monoxide concentration X_{CO}, was not included in Table 20 since it was almost always zero ppm during the steady-state portions of the tests.

The total (dry basis) flowrates, derived from helium tracer measurements Q_{AB} for the afterburner exhaust and Q_S for the stack gas, should be equivalent. Instead, Q_S is systematically higher than Q_{AB} by an average of 25.6 SCFM. Leakage of air into the scrubber system is a possible explanation for this observation.

Time Variations in Measured Quantities

Because a complete data set includes the important analyses of hot-zone and stack samples for POHCs and PICs, and since these samples are acquired over a time interval of one or more hours, giving a time-integrated analytical result, maintenance of steady-state test conditions over this time interval is a critical testing requirement.

Table 21 indicates the deviations in each of 14 measured quantities from true steady-state conditions in each of the twenty runs, derived from the data at discrete clock times in Tables 14, 15, and 19. For each measured parameter i in test number j, the data in Tables 14, 15, and 19 list $N_{i,j}$ values of $X_{i,j,t}$ at discrete times t. The time averages in Table 20 are values of

$$\bar{X}_{i,j} = \frac{\sum_t X_{i,j,t}}{N_{i,j}} , N_{i,j} \quad 0.$$

TABLE 21. TIME VARIATIONS IN MEASURED QUANTITIES

	Measured Quantity	Total Data Points	Overall Average	Degrees of Freedom	Pooled Standard Deviation	Relative Standard Deviation
W	Mol Percent H_2O in Air	69	2.377	49	0.121	0.0511
Q_K	Kiln Exh., Dry SCFM	46	276.0	31	15.2	0.0549
Q_{AB}	AB Exh., Dry SCFM	64	581.5	46	21.1	0.0362
Q_S	Stack Exh., Dry SCFM	71	619.4	51	19.6	0.0316
V_K	Kiln Vac., in H_2O	126	0.0418	106	0.0101	0.241
P_K	Propane to Kiln, SCFM	127	7.384	107	0.554	0.0750
P_{AB}	Propane to AB, SCFM	127	9.676	107	0.441	0.0456
A_{KB}	Kiln Burner Air, SCFM	126	246.9	106	16.6	0.0673
A_{AB}	AB Burner Air, SCFM	126	314.0	106	7.2	0.0229
X_{O_2}	Stack O_2, Dry Mol %	117	9.19	98	0.46	0.0502
X_{CO_2}	Stack CO_2, Dry Mol %	117	7.39	98	0.25	0.0332
θ_K	Kiln Temp., °F	127	1504	107	29	0.0192
θ_{AB}	AB Temp., °F	127	2013	107	18	0.0091
θ_X	AB Exhaust Temp., °F	126	1862	106	15	0.0081

The first column in Table 21 lists values of the total number of data points, $\sum_j N_{i,j}$, and the second column is the overall average, $M_i = \sum_{jt}\sum X_{i,j,t} \quad \sum_j N_{i,j}$. In the third column are the total number of degrees of freedom, $\sum_j (N_{i,j}-1)$, $N_{i,j} \quad 0$.

The pooled standard deviation in the fourth column of Table 21 is calculated from

$$(S_{pooled})_i^2 = \frac{\sum_{jt}\sum (X_{i,j,t} - \bar{X}_{i,j})^2}{\sum_j (N_{i,j}-1)}$$

and the relative standard deviation in the last column is $(S_{pooled})_i / M_i$.

Table 21 shows that the conditions were in fact close to steady state during each test. Except for V_K, the kiln vacuum, no experimental parameters had a relative standard deviation of greater than 7.5 per cent.

Another observation made by inspecting the data of Table 21 is that the afterburner conditions were apparently more stable than the kiln conditions. The relative standard deviations for propane flow, combustion air flow, and temperature were (respectively) 4.6 per cent, 2.3 per cent, and 0.9 per cent for the afterburner; compared to 7.5 per cent, 6.7 per cent, and 1.9 per cent for the kiln.

Combustion Stoichiometry

The quantitation of the combustion stoichiometry would be straightforward, except that the total quantity of air introduced into the system is not directly measurable. The rotary kiln operates with a mechanical seal on each end of the rotating drum, and the kiln is maintained (by operational intent) at a negative pressure. The air inadvertently admitted into the rotary kiln combustor cannot be regarded as of insignificant magnitude with respect to the measured airflow to the kiln burner. Instead, the total airflow must be inferred from other measurements, such as the total system flowrates derived from helium tracer measurements, or from measurements downstream in the process of oxygen, carbon dioxide, or water vapor concentrations. This situation requires a calculational procedure quantitatively relating the composition and streamflow of combustion products to the flowrates of materials fed (either intentionally or inadvertently) into the system.

In an excess of air, the reactions proceeding in the rotary kiln combustion chamber are:

(A) Propane Combustion, $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

(B) Toluene Combustion, $C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$

(C) TCB Combustion, $C_6H_3Cl_3 + 6O_2 \rightarrow 6CO_2 + 3HCl$

(D) HCB Combustion, $C_6Cl_6 + \frac{9}{2}O_2 + 3H_2O \rightarrow 6CO_2 + 6HCl$

These reactions may be assumed to proceed to completion under the kiln conditions of greater than 30 per cent excess air and temperatures of 1230 to 1620°F. In the afterburner, additional propane is combusted according to reaction (A) above. This also may be assumed to proceed to completion, under afterburner conditions of greater than 30 per cent excess air and temperatures of 1650 to 2160°F.

Two additional reactions to consider are the equilibria between HCl and Cl_2 and $Cl\cdot$:

(E) $2HCl + \frac{1}{2}O_2 \rightleftharpoons Cl_2 + H_2O$

(F) $Cl_2 \rightleftharpoons 2Cl\cdot$

These equilibria are evaluated later; for now, it is assumed that HCl is the dominant chlorine species at the range of conditions found in the kiln and afterburner.

The following flowrate quantities for the kiln and afterburner are measured (or derived from measured quantities):

P_K = Propane feed to kiln, SCFM
P_{AB} = Propane feed to afterburner, SCFM
A_{KB} = Combustion air feed to kiln burner, SCFM
A_{AB} = Combustion air feed to afterburner burner, SCFM
W = Mole fraction of moisture in air

TOL = Toluene feed to kiln, grams/hour

TCB = Trichlorobenzene feed to kiln, grams/hour

HCB = Hexachlorobenzene feed to kiln, grams/hour

Q_K = Total kiln exhaust gas flowrate (dry basis), SCFM, from helium tracer measurements

Q_{AB} = Total afterburner exhaust gas flowrate (dry basis), SCFM, from helium tracer measurements

In addition, A_{KL} denotes the unmeasured air leakage rate (in SCFM) into the kiln, through the mechanical seals.

For the gas flowrates above, a standard cubic foot is referenced to one atmosphere and 32°F, so that one pound mole occupies 359.05 standard cubic feet. The molecular weights for the organic liquids are:

Toluene	92.13
Trichlorobenzene	181.45
Hexachlorobenzene	284.79

Dry air composition is assumed to be:

Oxygen	20.99 mole per cent
Nitrogen	79.01 mole per cent

Table 22 lists the feed rates for each component to the kiln and to the afterburner, in terms of the eight measured parameters P_K, P_{AB}, A_{KB}, A_{AB}, W, TOL, TCB, and HCB, and the unknown parameter A_{KL}. Using the stoichiometry of Equations (A) through (D) the products of combustion may then be determined, as listed in Table 22, in terms of the same parameters.

The sum of the quantities for all the components, except for water vapor, in the exhaust from the kiln, gives the total calculated flowrate on a dry basis, Q_K, in SCFM:

$$\text{(G)} \quad Q_K = (A_{KB}+A_{KL})(1-W)-2P_K+\frac{(359.05)}{(60)(453.59)} - \left[\frac{2(TOL)}{92.13}+\frac{3(TCB)}{181.45}+\frac{7.5(HCB)}{284.79}\right]$$

Solving for the unknown quantity A_{KL}.

$$\text{(H)} \quad A_{KL} = \frac{Q_K+2P_K-\frac{359.05}{(60)(453.59)} - \left[\frac{2(TOL)}{92.13}+\frac{3(TCB)}{181.45}+\frac{7.5(HCB)}{284.79}\right]}{1-W} - A_{KB}$$

TABLE 22. COMBUSTION STOICHIOMETRY

Component	Feed to Kiln lb moles/hr	Feed to Afterburner lb moles/hr	Exhaust from Kiln lbs moles/hr	Exhaust from Afterburner lb moles/hr
Propane	$\frac{60\ (P_K)}{359.05}$	$\frac{60\ (P_{AB})}{359.05}$	0	0
Toluene	$\frac{(TOL)}{(453.59)(92.13)}$	0	0	0
Trichlorobenzene	$\frac{TCB}{(453.59)(181.45)}$	0	0	0
Hexachlorobenzene	$\frac{HCB}{(453.59)(284.79)}$	0	0	0
Oxygen	$\frac{60(A_{KB}+A_{KL})(0.2099)(1-M)}{359.05}$	$\frac{60(A_{AB})(0.2099)(1-M)}{359.05}$	$\frac{60(A_{KB}+A_{KL})(0.2099)(1-M)}{359.05} - \frac{(5)(60)(P_K)}{359.05}$ $- \frac{9(TOL)}{(453.59)(92.13)} - \frac{6(TCB)}{(453.59)(181.45)} - \frac{4.5\ (HCB)}{(453.50)(284.79)}$	$\frac{60(A_{KB}+A_{KL}+A_{AB})(0.2099)(1-M)}{359.05} - \frac{5(60)(P_K+P_{AB})}{359.05} -$ $\frac{9(TOL)}{(453.56)(92.13)} - \frac{6(TCB)}{(453.59)(181.45)} - \frac{4.5\ (HCB)}{(453.59)(284.79)}$
Nitrogen	$\frac{60(A_{KB}+A_{KL})(0.7901)(1-M)}{359.05}$	$\frac{60(A_{AB})(0.7901)(1-M)}{359.05}$	$\frac{60(A_{KB}+A_{KL})(0.7901)(1-M)}{359.05}$	$\frac{60(A_{KB}+A_{KL}+A_{AB})(0.7901)(1-M)}{359.05}$
Water Vapor	$\frac{60(A_{KB}+A_{KL})(M)}{359.05}$	$\frac{60(A_{AB})(M)}{359.05}$	$\frac{60(A_{KB}+A_{KL})(M)}{359.05} + \frac{(4)(60)(P_K)}{359.05}$ $+ \frac{(4)(TOL)}{(453.59)(181.45)} - \frac{(3)(HCB)}{(453.59)(284.79)}$	$\frac{60(A_{KB}+A_{KL}+A_{AB})(M)}{359.05} + \frac{(4)(60)(P_K+P_{AB})}{359.05} +$ $\frac{4(TOL)}{(453.59)(181.45)} - \frac{3(HCB)}{(453.59)(284.79)}$
Carbon Dioxide	0	0	$\frac{3(60)(P_K)}{359.05} + \frac{7(TOL)}{(453.59)(92.13)} + \frac{6(TCB)}{(453.59)(181.45)}$ $+ \frac{6(HCB)}{(453.59)(284.79)}$	$\frac{3(60)(P_K+P_{AB})}{359.05} + \frac{7(TOL)}{(453.59)(92.13)} + \frac{6(TCB)}{(453.59)(181.45)}$ $+ \frac{6(HCB)}{(453.59)(284.79)}$
Hydrogen Chloride	0	0	$\frac{(3)(TCB)}{(453.59)(181.45)} + \frac{6(HCB)}{(453.59)(284.79)}$	$\frac{3(TCB)}{(453.59)(181.45)} + \frac{6(HCB)}{(453.59)(284.79)}$

Similarly, the quantities (except for water vapor) in the afterburner exhaust may be summed to give the total calculated flowrate (dry basis), Q_{AB}, in SCFM:

$$(I)\quad Q_{AB} = (A_{KB}+A_{KL}+A_{AB})(1-W) - 2(P_K+P_{AB}) + \frac{(359.05)}{(60)(453.59)}\left[-\frac{2(TOL)}{92.13} + \frac{3(TCB)}{181.45} + \frac{7.5(HCB)}{284.79}\right],\ \text{or}$$

$$(J)\quad A_{KL} = \frac{Q_{AB}+2(P_K+P_{AB}) - \frac{(359.05)}{(60)(453.59)} - \left[\frac{2(TOL)}{92.13} + \frac{3(TCB)}{181.45} + \frac{7.5(HCB)}{284.79}\right]}{1-W} - A_{KB} - A_{AB}$$

The unknown kiln leakage airflow A_{KL} may therefore be determined in two ways: from the experimental value of Q_K using Equation (H), or from the experimental value of Q_{AB} using Equation (J). Both Q_K and Q_{AB} are determined using the helium tracer technique, but are measured independently. Table 23 lists values for A_{KL} determined both ways for each of the runs. The average value for A_{KL} is approximately the same whether Q_K and Equation (H) was used (47.8 SCFM), or whether Q_{AB} and Equation (J) was used (50.3 SCFM). The standard deviation is large in either case, but is not quite as large (31.7 SCFM) when Q_{AB} was used than when Q_K was used (47.2 SCFM). Table 23 also lists, for each run, the average of the two calculated values for A_{KL}. The resulting standard deviation of these values is 28.9 SCFM, not significantly different from the 31.7 SCFM obtained when using Q_{AB} and Equation (J) alone. For succeeding analyses, the values of A_{KL} derived from Q_{AB} and Equation (J) were therefore adopted. These values are listed in Table 20. Supporting evidence for the choice of Q_{AB} as a primary measurement is the relatively close correspondence between Q_{AB} and its redundant but independent measurement Q_S, the stack exhaust flowrate (dry basis).

The selection of A_{KL} as derived from the measured values of Q_{AB} implies that the measured values for Q_K should be rejected. To make the data set of Table 20 internally consistent, alternate calculated values for Q_K (labelled as Q_{KC}) were derived from Q_{AB}:

TABLE 23. CALCULATION OF AIR LEAKAGE INTO THE KILN

Test Date	Run	Measured SCFM		Calculated A_{KL}, SCFM			Calc. Q_{KC} SCFM
		Q_K	Q_{AB}	From Q_K Eq. H	From Q_{AB} Eq. J	Avg.	Eq. K
0817	1	265.2	612.0	28.5	58.6	43.6	294.4
0817	2	291.2	518.3	129.0	35.8	82.4	200.6
0819	1	189.2	451.5	51.2	0.6	25.9	140.0
0819	2	171.5	453.7	32.9	18.4	25.7	157.4
0823	1	251.5	487.4	112.2	34.2	73.2	173.7
0823	2	187.9	512.6	49.2	74.4	61.8	212.5
0825	1	269.7	610.6	- 27.4	7.5	-10.0	303.6
0825	2	259.7	606.3	23.3	70.0	46.7	305.1
0901	1	303.8	589.4	109.4	83.7	96.6	278.8
0901	2	271.0	512.0	109.7	42.4	76.1	205.5
0906	1	246.8	567.7	- 9.5	- 1.7	- 5.6	254.4
0906	2	—	584.5	—	66.3	66.3	274.3
0908	1	274.2	600.6	40.1	59.2	49.7	292.9
0908	2	—	561.9	—	55.2	55.2	253.5
0913	1	—	—	—	—	—	—
0913	2	—	—	—	—	—	—
0922	1	343.9	739.2	25.8	91.5	58.7	408.9
0922	2	—	657.1	—	44.0	44.0	329.1
0926	1	350.7	733.2	39.3	115.8	77.6	425.9
0926	2	306.6	670.9	2.7	49.2	26.0	352.2
Average				47.8	50.3	49.7	
Std. Dev.				47.2	31.7	28.9	

Subtracting Equation (G) from Equation (I),

$$Q_{AB} - Q_K = A_{AB}(1-W) - 2P_{AB}; \text{ or}$$

$$\text{(K)} \quad Q_{KC} \equiv Q_K = Q_{AB} + 2P_{AB} - A_{AB}(1-W).$$

These values for Q_{KC} are listed in Table 23 and in Table 20. Table 20 also lists the ratio Q_K/Q_{KC}, which varies on both sides of unity.

Figure 9 shows a weak correlation between the calculated air leakage rate into the kiln, A_{KL} (calculated from Q_{AB} using Equation (J)), and the calculated kiln exhaust flowrate, Q_{KC}. The least-squares line shown is $A_{KL} = 0.256\ Q_{KC} - 19.0$, and the correlation coefficient is 0.65. One possible explanation for this apparent dependence is that the velocity head of higher kiln gas flowrates creates a lower pressure in the kiln, thereby increasing the leakage rate of outside air into the kiln through the mechanical seals.

Table 20 also lists the stoichiometric ratio of oxygen to propane in the kiln burner and in the afterburner burner, calculated from

$$OF_K = \frac{(0.2099)(1-W)(A_{KB})}{5(P_K)}$$

and

$$OF_{AB} = \frac{(0.2099)(1-W)(A_{AB})}{5(P_{AB})}$$

Values of OF_K and OF_{AB} of unity correspond to zero per cent excess air. The per cent excess air is simply 100 (OF_K-1) or 100 $(OF_{AB}-1)$.

Figure 10 is a graphical representation of the stoichiometry in the burners: combustion air flowrate is plotted vs. propane flowrate, with reference lines at several excess air percentages. Each burner operated at about 35 per cent excess air at higher firing settings, and at 40 to 80 per cent excess air at lower settings, although the kiln burner operated over a much wider range of propane flowrates.

Material Balances

Table 24 is a material balance for each run, with quantities in pound moles per hour. The time-averaged measured quantities of Table 20, along with

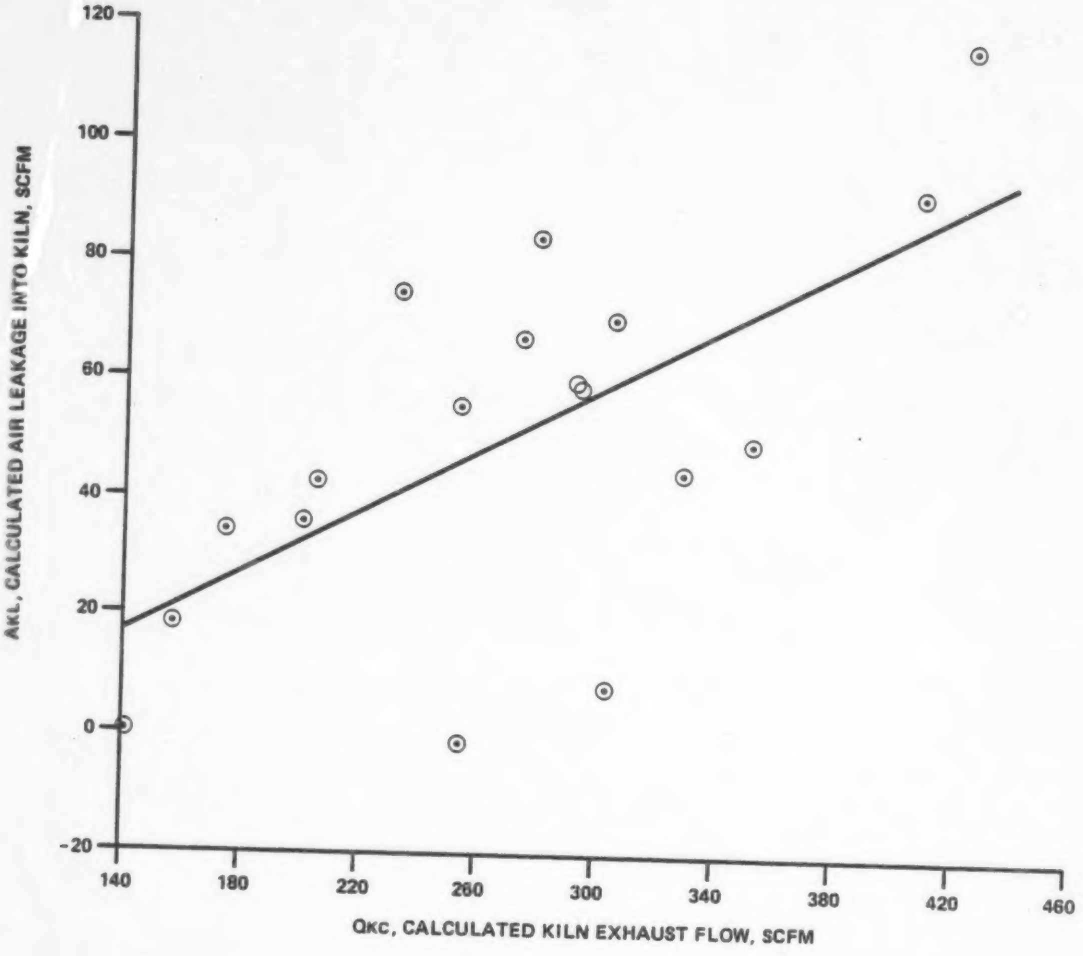

FIGURE 9
EFFECT OF TOTAL KILN FLOW UPON LEAKAGE

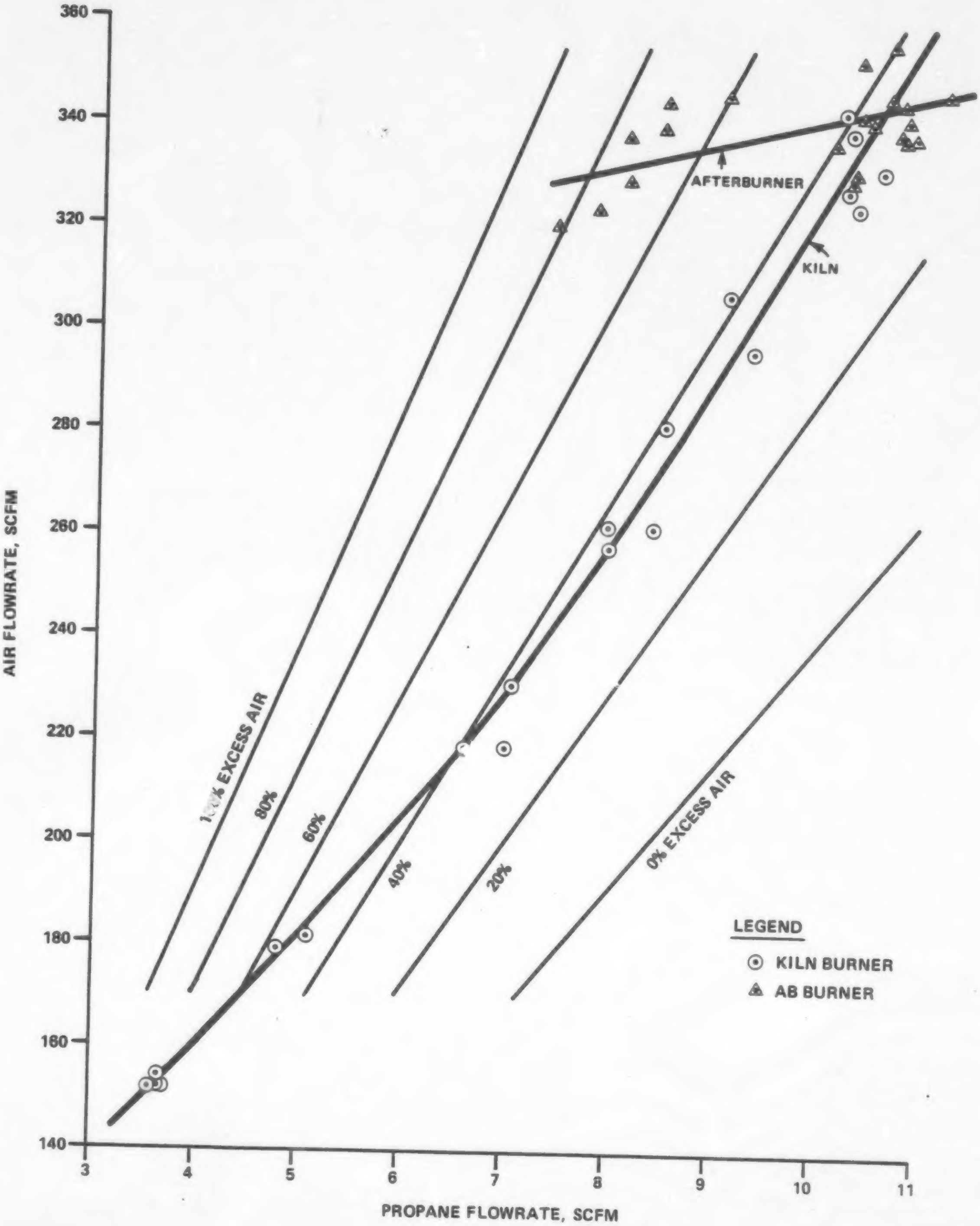

FIGURE 10
AIR AND PROPANE FLOWRATES IN THE BURNERS

TABLE 24. MATERIAL BALANCES, POUND-MOLES PER HOUR

	Test Date & Run Start Time Stop Time	0817-1 0945 1130	0817-2 1131 1415	0819-1 0945 1120	0819-2 1121 1230	0823-1 0945 1114	0823-2 1115 1245	0825-1 1030 1210	0825-2 1211 1350	0901-1 1034 1130	0901-2 1139 1215
Feed to Kiln (Including AKL)	Propane	1.329	0.852	0.597	0.616	0.611	0.620	1.714	1.404	1.169	0.802
	Toluene x 10^9	0	58.84	57.50	57.50	58.84	58.84	58.84	58.84	143.53	57.41
	HCB x 10^9	0	0	0.774	0.774	0	0	0	0	0	0
	TCB x 10^9	0	0	0	0	0	0	0	0	3.038	1.215
	O_2	10.886	7.420	5.106	5.801	6.373	7.738	11.392	11.317	10.328	7.568
	N_2	40.976	27.929	19.520	21.837	23.989	29.126	42.882	42.597	38.876	28.486
	H_2O	1.563	1.015	0.745	0.803	0.786	0.921	1.626	1.466	1.296	0.994
Feed to Afterburner	Propane	1.522	1.419	1.360	1.244	1.415	1.310	1.797	1.723	1.812	1.821
	O_2	11.778	11.740	11.498	10.914	11.598	11.077	11.521	11.289	11.654	11.514
	N_2	44.334	44.190	43.282	41.083	43.657	41.696	43.367	42.949	43.868	43.340
	H_2O	1.691	1.605	1.652	1.511	1.430	1.319	1.645	1.462	1.462	1.512
Kiln Exhaust (Calculated from Feed)	CO_2	3.987	2.968	2.198	2.255	2.245	2.272	5.554	4.624	4.530	2.815
	O_2	4.241	2.630	1.680	2.200	2.788	4.108	2.292	3.767	3.173	3.034
	N_2	40.976	27.929	19.520	21.837	23.989	29.126	42.882	42.597	38.876	28.486
	HCl x 10^9	0	0	4.644	4.644	0	0	0	0	9.114	3.645
	Subtotal Dry	49.204	33.527	23.403	26.297	29.022	35.506	50.728	50.988	46.588	34.339
	H_2O	6.879	4.658	3.361	3.495	3.465	3.636	8.717	7.317	6.546	4.432
	Total	56.083	38.185	26.764	29.792	32.487	39.142	59.445	58.305	53.134	38.771
Afterburner Exhaust (Calculated from Feed)	CO_2	8.553	7.225	6.278	5.987	6.490	6.202	10.945	9.793	9.966	8.278
	O_2	8.409	7.275	6.378	6.894	7.311	8.635	4.828	6.441	5.767	5.433
	N_2	85.310	72.119	62.802	62.920	67.646	70.822	86.249	85.091	82.744	71.826
	HCl x 10^9	0	0	4.644	4.644	0	0	0	0	9.114	3.645
	Subtotal Dry	102.272	86.619	75.463	75.086	81.447	85.659	102.022	101.325	98.486	85.551
	H_2O	14.658	11.939	10.453	9.982	10.555	10.195	17.550	15.671	15.256	13.228
	Total	116.930	98.558	85.916	85.788	92.002	95.854	119.572	116.996	113.742	98.779

	Test Date & Run Start Time Stop Time	0906-1 1026 1146	0906-2 1147 1325	0908-1 1045 1216	0908-2 1217 1410	0913-1 1030 1217	0913-2 1218 1330	0922-1 1100 1220	0922-2 1221 1440	0926-1 1000 1140	0926-2 1230 1300
Feed to Kiln (Including AKL)	Propane	1.420	1.178	1.331	1.104	1.730	1.562	1.709	1.522	1.719	1.772
	Toluene x 10^9	51.71	51.71	44.58	44.58	0	0	0	0	0	0
	HCB x 10^9	0	0	0	0	0	0	0	0	0	0
	TCB x 10^9	6.075	6.075	12.150	12.150	50.156	50.156	0	0	0	0
	O_2	9.537	10.133	10.843	9.365	—	—	15.059	12.183	15.661	13.098
	N_2	35.900	38.142	40.814	35.253	—	—	56.687	45.860	58.953	49.305
	H_2O	1.235	1.356	1.251	1.051	—	—	0.745	0.561	1.269	1.131
Feed to Afterburner	Propane	1.806	1.752	1.807	1.694	1.776	1.738	1.785	1.733	1.359	1.877
	O_2	11.747	11.617	11.551	11.528	11.857	11.753	12.334	12.232	11.350	11.965
	N_2	44.218	43.728	43.480	43.393	44.632	44.239	46.429	46.043	42.725	45.039
	H_2O	1.521	1.555	1.332	1.294	1.230	1.076	0.610	0.564	0.920	1.032
Kiln Exhaust (Calculated from Feed)	CO_2	4.658	3.932	4.378	3.697	5.491	4.987	5.127	4.566	5.157	5.316
	O_2	1.935	3.741	3.714	3.371	—	—	6.514	4.573	7.066	4.238
	N_2	35.900	38.142	40.814	35.253	—	—	56.687	45.860	58.953	49.305
	HCl x 10^9	18.225	18.225	36.450	36.450	150.468	150.468	0	0	0	0
	Subtotal Dry	42.511	45.833	48.942	42.357	—	—	68.328	54.999	71.176	58.859
	H_2O	7.122	6.275	6.753	5.645	—	—	7.581	6.649	8.145	8.219
	Total	49.633	52.108	55.695	48.002	—	—	75.909	61.648	79.321	67.078
Afterburner Exhaust (Calculated from Feed)	CO_2	10.076	9.188	9.799	8.779	10.819	10.201	10.482	9.765	9.234	10.947
	O_2	4.652	6.598	6.230	6.429	—	—	9.923	8.140	11.621	6.818
	N_2	80.118	81.848	84.294	78.646	—	—	103.116	91.903	101.678	94.344
	HCl x 10^9	18.225	18.225	36.450	36.450	150.468	150.468	0	0	0	0
	Subtotal Dry	94.864	97.652	100.359	93.890	—	—	123.521	109.808	122.533	112.109
	H_2O	15.867	14.838	15.313	13.715	—	—	15.331	14.145	14.501	16.759
	Total	110.731	112.490	115.672	107.605	—	—	138.852	123.953	137.034	128.868

the calculated quantities A_{KL} and Q_{KC} (the latter used instead of the measured Q_K), were the basis for the values in Table 24. The expressions of Table 22 were used to generate the numerical entries in Table 24.

Two comparisons between pairs of redundant measurements have already been made. One is the comparison of Q_K, the measured total flowrate of the exhaust gas from the rotary kiln (dry basis), with Q_{KC}, calculated from independent measurements of the afterburner exhaust flowrate (Q_{AB}) and of the flowrates of propane (P_{AB}) and combustion air (A_{AB}) to the afterburner. From the data of Table 20, the root-mean-square (rms) difference between Q_K and Q_{KC} is 50.9 SCFM, which is 19.1 per cent of the overall mean. Since the average difference (Q_K-Q_{KC}) avg. is only -1.5 SCFM, there appears to be no significant bias between the two determinations over the entire test series. However, when compared to the relative standard deviation (rsd) of Q_K within each test (from Table 21) of 5.5 per cent, and with the within-test rsd values for the parameters used to calculate Q_{KC} (3.6 per cent for Q_{AB}, 4.6 per cent for P_{AB}, and 2.3 per cent for A_{AB}), the much higher rms difference between Q_K and Q_{KC} indicates that there may be a sizable test-to-test variability in one or more of the measured parameters.

A second comparison between pairs of redundant measurement is that between Q_{AB}, the afterburner exhaust, and Q_S, the stack exhaust, both on a dry basis. As noted previously, Q_S is systematically higher than Q_{AB} by an average of 25.6 SCFM, which is 4.3 per cent of the overall mean value. Leakage of air into the scrubber system is a possible explanation for the observed bias.

The values shown in Table 24 for the afterburner exhaust gas quantities are those calculated from the feed quantities. These may be directly compared to the analytical results obtained from gas samples. Table 20 lists X_{O_2} and X_{CO_2}, the measured oxygen and carbon dioxide concentrations in the stack gas, and Table 16 lists values for the measured water vapor concentration in the afterburner exhaust gas.

The measured quantities are summarized in Table 25. For comparison, the comparable calculated values (from Table 24) are also included. The "measured" carbon dioxide flowrate, in pound moles per hour, is:

$$\left(\frac{X_{CO_2}}{100}\right)\left(\frac{60\ Q_S}{359.05}\right)$$

For the "measured" oxygen flowrate, the quantity as determined in the stack sample was corrected for the apparent leakage of air into the scrubber system:

$$\left(\frac{X_{O_2}}{100}\quad\frac{60\ Q_S}{359.05}\right) - (0.2099)(60)\ \frac{(Q_S - Q_{AB})}{(359.05)}$$

The "measured" water vapor is calculated from the values in Table 16:

$$\left(C_{AB}^{M}\right)\ \left(Q_{AB}\right)$$

Also listed in Table 25 are the differences between the measured and calculated flowrates. All 19 of the measured CO_2 flowrates are less than the comparable values calculated from feed quantities; all 8 of the measured water vapor flowrates are less than the comparable calculated values; and 17 of 18 of the measured O_2 flowrates are greater than the comparable calculated values. The mean differences are:

Δ CO_2,	- 1.46 lb moles/hr
Δ H_2O,	- 4.72 lb moles/hr
Δ O_2,	+ 1.35 lb moles/hr

Two explanations may be offered for consistent differences in the observed directions:

1. If the propane fed to the kiln and/or the afterburner were in actuality less than the measured P_K and/or P_{AB}. The CO_2 and H_2O products of combustion would then be smaller than indicated in Table 24, and less O_2 would be consumed leaving a greater O_2 residual than indicated in Table 24.

TABLE 25. ALTERNATE MEASURES OF EXHAUST GAS CONSTITUENTS

Test Date	Run	Carbon Dioxide Flowrate lb moles/hr			Oxygen Flowrate lb moles/hr					Water Vapor Flowrate lb moles/hr			Total Propane Feed, lb moles/hr		Total Oxygen to Burners, lb moles/hr
		Meas, M	Calc, C	Δ=M-C	Stack	Leakage	Meas, M	Calc, C	Δ=M-C	Meas, M	Calc,	Δ=M-C	From Propane Flowmeters	From Measured Exhaust CO₂	
0817	1	7.78	8.55	-0.77	10.41	0.64	9.77	8.41	1.36	11.20	14.66	-3.46	2.851	2.593	20.668
0817	2	6.45	7.23	-0.81	9.57	1.00	8.57	7.28	1.29	7.98	11.94	-3.96	2.271	2.013	17.939
0819	1	5.48	6.28	-0.80	9.00	1.5	7.85	6.38	1.47	6.59	10.22	-3.63	1.957	1.691	16.664
0819	2	5.52	5.99	-0.47	9.70	1.92	7.78	6.89	0.89				1.860	1.704	16.088
0823	1	5.97	6.49	-0.52	9.45	0.95	8.50	7.31	1.19	7.05	10.56	-3.51	2.026	1.853	16.863
0823	2	5.89	6.20	-0.31	10.53	1.12	9.41	8.64	0.77	7.67	10.20	-2.53	1.930	1.826	16.269
0825	1	8.94	10.95	-2.01	7.23	1.19	6.04	4.83	1.21	—	17.55	—	3.511	2.843	22.657
0825	2	8.02	9.79	-1.77	7.55	0.11	7.44	6.44	1.00	—	15.67	—	3.127	2.536	20.215
0901	1	7.81	9.97	-2.16	8.84	0.39	8.45	5.77	2.68	7.33	14.24	-6.91	2.981	2.262	19.121
0901	2	3.11	8.28	-5.17	13.02	0.33	12.69	5.44	7.25				2.623	0.900	17.634
0906	1	8.25	10.08	-1.83	6.73	1.04	5.69	4.65	1.04	7.89	15.35	-7.46	3.226	2.617	21.342
0906	2	8.02	9.19	-1.17	7.15	2.48	4.67	6.60	-1.93				2.930	2.541	19.488
0908	1	8.44	9.80	-1.36	8.07	0.95	7.12	6.23	0.89	8.21	14.51	-6.30	3.138	2.685	20.367
0908	2	8.02	8.78	-0.76	7.99	1.45	6.54	6.43	0.11				2.798	2.545	19.002
0913	1	8.49	10.82	-2.33	9.19	—	—	—	—	—	—	—	3.506	2.713	22.966
0913	2	—	10.20	—	—	—	—	-	—	—	—	—	3.300	—	21.939
0922	1	9.72	10.48	-0.76	10.53	0.29	10.24	9.92	0.32	—	15.33	—	3.494	3.240	24.217
0922	2	8.78	9.77	-0.99	10.06	1.20	8.86	8.14	0.72	—	14.15	—	3.255	2.927	22.887
0926	1	7.80	9.23	-1.43	13.17	(0)	13.17	11.62	1.55	—	14.50	—	3.078	2.600	23.018
0926	2	8.72	10.95	-2.23	9.37	(0)	9.37	6.82	2.55	—	16.76	—	3.649	2.907	23.369

2. If the exhaust gas samples were diluted with air prior to analysis. The oxygen in the dilution air would result in a greater apparent measured oxygen content, and the diluent would result in smaller apparent measured CO_2 and H_2O contents. Sample dilution with air could occur if the vacuum sampling system leaked or if it were not completely purged.

To investigate the first possible explanation, i.e., that the propane flowrates are providing erroneously high readings, an alternate total propane feed rate was back-calculated for each run from the measured carbon dioxide flowrate, using the material balance relationships in Table 22. Both sets of alternate total propane feed rates are listed in Table 25, and are graphically compared in Figure 11. The mean difference between the alternate data sets is 0.485 pound moles of propane per hour, which is 18.6 per cent of the overall average.

For all runs except 0901-1 and especially 0901-2, the points on Figure 11 all fall within a reasonable range below the ideal 45-degree line. The question of which set of propane feed rate data (the one based upon propane flowmeter readings or the one based upon stack CO_2 measurements) should be honored as primary data remains unresolved, without the two runs 0901-1 and especially 0901-2.

If the data set based upon stack CO_2 measurements is the correct one, then the total propane feed rate for Run 0901-2 would be clearly inconsistent with the propane feed rates for five other late runs* where the kiln and afterburner temperatures were maintained at approximately 1600°F and 2100°F (respectively). Using the data set based upon stack CO_2 measurements, the indicated total propane feed rate for Run 0901-2 is 0.90 pound moles per hour, much smaller than the values for Runs 0825-2, 0906-2, 0908-2, 0922-2, and 0926-2, which range from 2.54 to 2.93 pound moles per hour.

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*The propane feed rate is consistently lower for the later run of each testing day, because the combustion chamber insulation and walls have already been appreciably heated.

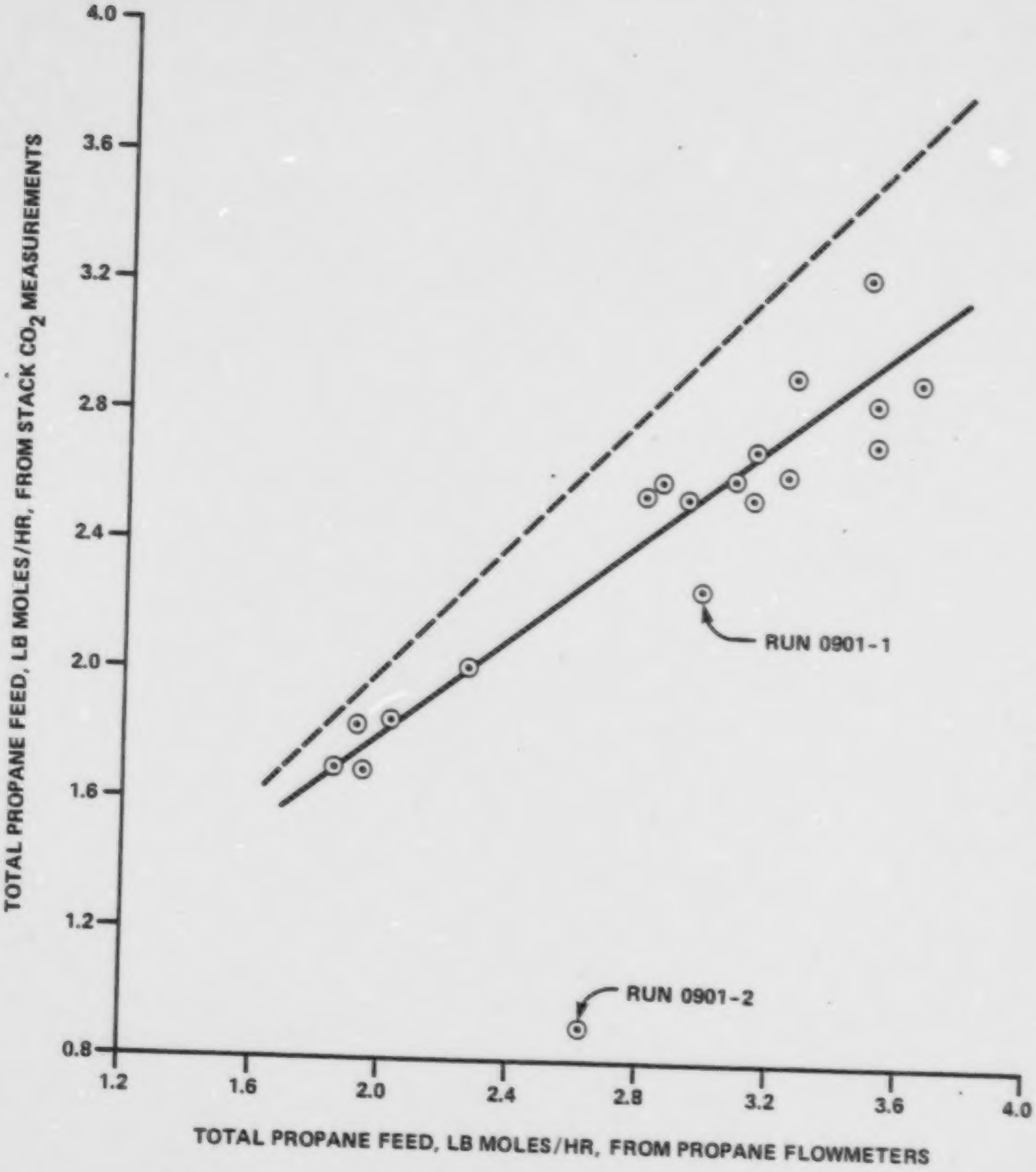


FIGURE 11

COMPARISON OF ALTERNATE PROPANE FLOWRATES

An additional argument for the invalidity of the total propane flowrate for Run 0901-2, based upon stack CO_2 measurements, is that the burner oxygen-to-propane proportion for this run is much too large. Table 25 lists the total oxygen flowrate to both burners for each run, and Figure 12 graphically compares the alternate propane flowrates to the burner oxygen flowrate. For propane data based upon flowmeter readings, Figure 12 indicates a range of 35 to 70 per cent excess oxygen for all runs. For the alternate propane data based upon stack CO_2 measurements, Figure 12 indicates a range of 50 to 100 per cent excess oxygen, except that Run 0901-2 has an indicated excess oxygen of 392 per cent. Since the valves regulating propane flow and air flow to each burner are mechanically linked, the propane data for Run 0901-2 (based upon stack CO_2 measurements) is most assuredly invalid, supporting the previous argument based upon the propane requirements to sustain high kiln and afterburner temperatures.

If the same mechanism caused the obviously anomalous data point for Run 0901-2 as was responsible for the systematic (but less dramatic) differences between the two data sets, doubt is cast upon the validity of the entire data set of propane feed rates based upon stack CO_2 measurements. The alternate data set, based upon propane flowmeter data, is therefore identified as primary data.

By inference, there apparently is leakage of air into the vacuum sampling system, diluting the exhaust gas samples and causing erroneous analytical results.

Actual Volumetric Flowrates, Velocities, and Residence Times

The material balance data of Table 24 lists time averages for the total flowrates (calculated from measured feed rates) for each run in the exhaust from the kiln and in the exhaust from the afterburner. Time averages of measured temperatures in the kiln (θ_K), in the afterburner (θ_{AB}), and in the afterburner exhaust (θ_X) are listed in Table 20.

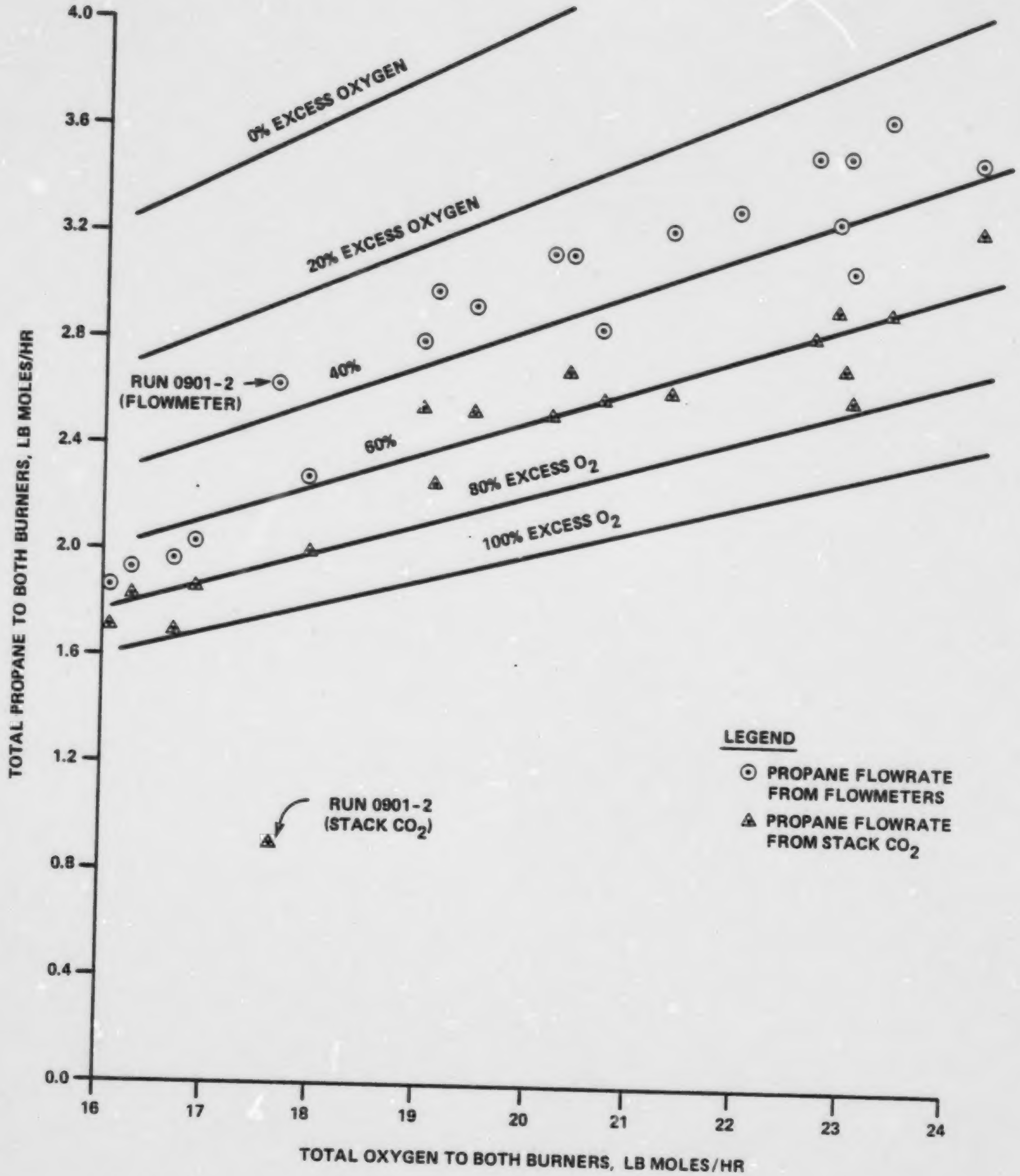


FIGURE 12

PROPANE VS. OXYGEN FLOW IN BURNERS

Table 26 lists total flowrates in actual cubic feet per second, calculated by:

$$\left(\frac{459.7 + \theta}{459.7 + 32}\right)\left(\frac{359.05}{3,600}\right) \text{(Total Flowrate, lb moles/hr)}$$

where θ is either θ_K, θ_{AB}, or θ_X, °F. Also listed is the flowrate in the kiln-to-afterburner transfer duct, which is the same as that in the kiln, since the temperature in the transfer duct (not directly measured) is assumed equivalent to θ_K.

Table 26 lists the superficial linear velocities and the superficial residence times in each of the four sections (kiln, transfer duct, afterburner, and exhaust duct), based upon the listed volumetric flowrates, and the smallest internal cross-sectional areas and the internal volumes listed in Table 12.

Since the temperatures of the exhaust gases in the venturi inlet duct were not directly measured, this section of the incinerator is not addressed in this dicussion (later heat transfer calculations will be used to determine the temperature profile).

The data of Table 26 show low linear velocities, 0.7 to 2.4 feet per second; and high gaseous residence times, 2.9 to 9.5 seconds; in the rotary kiln combustion chamber. The linear velocities in the kiln-to-afterburner transfer duct are in the range of 4.8 to 16.0 feet per second, are 4.8 to 8.9 feet per second in the afterburner, and are 24 to 42 feet per second in the afterburner exhaust duct. The afterburner residence times range from 1.0 to 1.9 seconds, with an additional 0.2 to 0.3 seconds at high temperatures in the exhaust duct.

Transport Properties and Reynolds Numbers

The Reynolds number, N_{Re}, is the dimensionless ratio defined as

$$N_{Re} = \frac{DU\rho}{\mu}, \quad \text{where}$$

D = Hydraulic diameter, ft, given in Table 12

U = Superficial velocity, ft/sec, given in Table 26

ρ = Fluid density, lbm/ft^3

μ = Viscosity, lbm/ft-sec

TABLE 26. VOLUMETRIC FLOWRATES, VELOCITIES, AND RESIDENCE TIMES

Test Date	Run	Total Volumetric Flowrates, acfs				Superficial Linear Velocities, fps				Superficial Residence Times, Seconds			
		Kiln	Tr. Duct	AB	Ex. Duct	Kiln	Tr. Duct	AB	Ex. Duct	Kiln	Tr. Duct	AB	Ex. Duct
0817	1	21.20	21.20	57.72	53.83	1.62	10.67	7.14	35.9	4.30	0.27	1.29	0.21
0817	2	14.48	14.48	48.51	45.37	1.11	7.29	6.00	30.2	6.29	0.39	1.53	0.25
0819	1	9.57	9.57	39.16	36.05	0.73	4.82	4.84	24.0	9.52	0.59	1.90	0.32
0819	2	11.36	11.36	38.71	36.02	0.87	5.72	4.79	24.0	8.02	0.50	1.92	0.32
0823	1	11.19	11.19	42.13	38.64	0.85	5.63	5.21	25.8	8.15	0.51	1.77	0.30
0823	2	14.15	14.15	43.41	40.42	1.08	7.12	5.37	26.9	6.44	0.40	1.71	0.29
0825	1	24.58	24.58	63.44	59.25	1.88	12.38	7.85	39.5	3.71	0.23	1.17	0.20
0825	2	24.36	24.36	62.22	58.37	1.86	12.27	7.70	38.9	3.74	0.23	1.20	0.20
0901	1	22.20	22.20	59.40	55.57	1.70	11.18	7.35	37.0	4.11	0.25	1.25	0.21
0901	2	16.19	16.19	52.53	49.22	1.24	8.15	6.50	32.8	5.63	0.35	1.42	0.23
0906	1	20.65	20.65	58.12	54.37	1.58	10.40	7.19	36.2	4.41	0.27	1.28	0.21
0906	2	21.77	21.77	59.73	56.12	1.66	10.96	7.39	37.4	4.19	0.26	1.25	0.21
0908	1	23.26	23.26	61.18	57.38	1.78	11.71	7.57	38.3	3.92	0.24	1.22	0.20
0908	2	20.05	20.05	57.00	53.69	1.53	10.10	7.05	35.8	4.55	0.28	1.31	0.22
0913	1	—	—	—	—	—	—	—	—	—	—	—	—
0913	2	—	—	—	—	—	—	—	—	—	—	—	—
0922	1	31.79	31.79	71.76	68.26	2.43	16.01	8.88	45.5	2.87	0.18	1.04	0.17
0922	2	25.89	25.89	65.24	61.82	1.98	13.04	8.07	41.2	3.52	0.22	1.14	0.19
0926	1	29.33	29.33	58.78	57.25	2.24	14.77	7.27	38.2	3.11	0.19	1.27	0.20
0926	2	28.31	28.31	66.60	63.62	2.16	14.25	8.24	42.4	3.22	0.20	1.12	0.18

The density ρ for each of the gas mixtures (the kiln exhaust and the afterburner exhaust, assumed to be at one atmosphere) with composition listed in Table 24 is calculated by:

$$\rho = \frac{(MW_{avg})(459.7+32)}{(359.05)(459.7+\theta)}$$

where θ is either θ_K, θ_{AB}, or θ_x, °F;

where MW_{avg}, the average moleculare weight is

$$MW_{avg} = \frac{\sum_k m_k MW_k}{\sum_k m_k} \quad ; \qquad \text{and where}$$

MW_k and m_k are respectively, the molecular weight of constituent k and the flowrate of constituent k. Values of m_k and of $\sum_k m_k$ are in Table 24. Values for MW_k are:

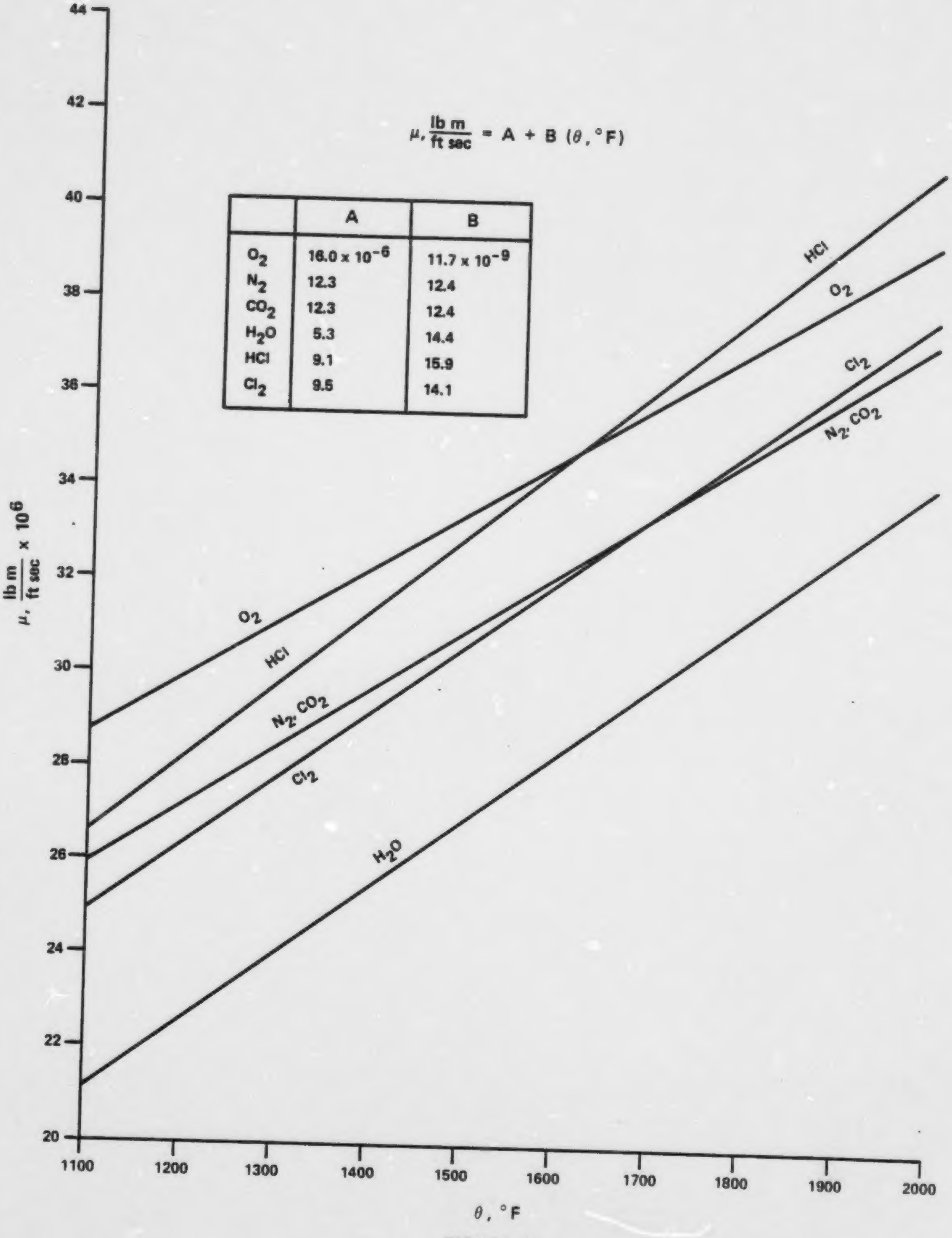
CO_2	44.010
O_2	32.000
N_2	28.016
HCl	36.461
H_2O	18.016

The viscosity data for the gaseous constituents at elevated temperatures were taken from a nomograph in the Chemical Engineer's Handbook,(6) were extrapolated from 1800°F, and were then converted for easier use into the graph and set of linear equations shown in Figure 13. The average viscosity for the mixture was then determined by

$$\mu = \frac{\sum_k m_k \mu_k}{\sum_k m_k} \quad ,$$

where μ_k for constituent k is evaluated at the appropriate temperature θ. Since (in Figure 13) $\mu_k = A_k + B_k\theta$,

$$\mu = \frac{\sum_k m_k A_k + \theta \sum_k m_k B_k}{\sum_k m_k} = A_{avg} + \theta\, B_{avg}$$



$$\mu, \frac{lb\ m}{ft\ sec} = A + B\ (\theta, °F)$$

	A	B
O_2	16.0×10^{-6}	11.7×10^{-9}
N_2	12.3	12.4
CO_2	12.3	12.4
H_2O	5.3	14.4
HCl	9.1	15.9
Cl_2	9.5	14.1

FIGURE 13
VISCOSITY VS. TEMPERATURE

Table 27 lists for each run; and separately for the kiln, the kiln-to-afterburner transfer duct (assumed to be at the same temperature as the kiln), the afterburner, and the afterburner exhaust duct; values of the average molecular weight MW_{avg}, of the gas density ρ, of the gas viscosity μ, and of the Reynolds number N_{Re}.

As in the previous section, the venturi inlet duct is not addressed in this discussion, since the gas temperatures were not directly measured.

Because the combustion gas composition is very similar from run-to-run, and is dominated by nitrogen, the transport properties do not vary over wide ranges. The average molecular weight range is 28.31 ± 0.14. The ranges for the average viscosity coefficients are A=11.7±0.3 and B=12.6±0.1.

The Reynolds numbers in the kiln range from 2,300 to 6,700, just in the transition zone between the laminar and turbulent flow regimes. Turbulence induced by the kiln burner would influence the kiln flow patterns. In the kiln-to-afterburner transfer duct, N_{Re} ranges from 5,100 to 14,800; coincidentally similar to that in the afterburner (7,800 to 13,100). Flow should be turbulent in this regime. Turbulent flow is expected in the afterburner exhaust duct, with Reynolds numbers ranging from 16,800 to 27,000.

System Pressure Profile

The elevation head, the velocity head, the friction loss, and the total pressure drop, in each item of equipment exposed to unquenched combustion gases, were calculated according to Table 28.

The symbols in Table 28 are:

H = head, inches of water

i = K,T,AB,X,V = subscripts for (respectively) the kiln, kiln-to-afterburner transfer duct, afterburner, afterburner exhaust duct, and the venturi inlet duct.

ρ_i = gas density, lbm/ft^3

ρ_w = density of water = 62.438 lbm/ft^3

U_i = velocity, ft/sec, from Table 26

g = 32.174 ft/sec^2

g_c = 32.174 lbm-ft/lbf-sec^2

Z_i = elevation, ft, with reference to kiln centerline:

Z_T = 2.19 ft (midpoint)

TABLE 27. TRANSPORT PROPERTIES AND REYNOLDS NUMBERS

Test Date	Run	MW_{avg}		ρ, lbm/ft³, X 10³			μ, lbm/ft-sec, X10⁶			N_{Re} = Reynolds Number			
		Kiln & Tr. Duct	AB & Ex. Duct	Kiln Tr. Duct	AB	Ex. Duct	Kiln & Tr. Duct	AB	Ex. Duct	Kiln	Tr. Duct	AB	Ex. Duct
0817	1	28.228	28.219	20.74	15.88	17.03	29.4	36.6	34.5	4,670	10,250	9,940	21,300
0817	2	28.314	28.271	20.74	15.95	17.06	29.5	36.5	34.5	3,190	6,980	8,420	17,900
0819	1	28.325	28.264	21.99	17.24	18.71	28.1	34.2	32.0	2,330	5,140	7,840	16,800
0819	2	28.349	28.289	20.65	17.41	18.72	29.6	34.0	32.0	2,480	5,440	7,870	16,800
0823	1	28.397	28.314	22.91	17.17	18.73	25.7	34.4	32.0	3,100	6,840	8,340	18,100
0823	2	28.434	28.346	21.84	17.39	18.67	28.6	34.1	32.2	3,370	8,450	8,790	18,700
0825	1	28.214	28.173	18.95	14.75	15.79	31.4	38.7	36.5	4,630	10,180	9,600	20,500
0825	2	28.287	28.235	18.81	14.75	15.72	32.0	38.9	36.9	4,470	9,820	9,360	19,900
0901	1	28.387	28.279	18.87	15.04	16.08	31.8	38.3	36.2	4,120	9,040	9,260	19,700
0901	2	28.386	28.237	18.88	14.75	15.74	31.9	38.9	36.8	3,000	6,570	7,810	16,800
0906	1	28.241	28.208	18.86	14.93	15.96	31.6	38.4	36.3	3,850	8,450	8,970	19,100
0906	2	28.308	28.238	18.82	14.77	15.72	31.9	38.9	36.9	4,000	8,810	9,000	19,100
0908	1	28.332	28.264	18.85	14.84	15.83	31.9	38.7	36.7	4,300	9,420	9,310	19,800
0908	2	28.358	28.287	18.85	14.83	15.75	31.9	38.8	36.9	3,690	8,130	8,640	18,300
0913	1	—	—	—	—	—	—	—	—	—	—	—	—
0913	2	—	—	—	—	—	—	—	—	—	—	—	—
0922	1	28.439	28.404	18.86	15.27	16.05	32.1	38.0	36.5	5,830	12,810	11,440	24,000
0922	2	28.418	28.396	18.79	14.99	15.82	32.1	38.6	36.9	4,730	10,400	10,050	21,200
0926	1	28.384	28.373	21.33	18.37	18.86	29.0	32.6	32.0	6,730	14,800	13,140	27,000
0926	2	28.310	28.285	18.63	15.20	15.92	32.1	37.9	36.5	5,120	11,260	10,600	22,200

TABLE 28. CALCULATIONS FOR SYSTEM PRESSURE PROFILE

		H_Z Elevation Head	H_U Velocity Head	H_F Friction Loss	H_T Total Head Loss
K	Rotary Kiln	0	$\left(12\,\frac{\rho_K}{\rho_W}\right)\left(\frac{U_K^2}{2gc}\right)$	$\left(12\,\frac{\rho_K}{\rho_W}\right)\left(4f_K\,\frac{L_K}{D_K}\right)\left(\frac{U_K^2}{2gc}\right)$	$\left(H_U\right)_K + \left(H_F\right)_K$
T	Kiln-to-Afterburner Transfer Duct	$\left(12\,\frac{\rho_T}{\rho_W}\right)\left(\frac{g}{gc}\,Z_T\right)$	$\left(12\,\frac{\rho_T}{\rho_W}\right)\left(\frac{U_T^2}{2gc}\right)$	$\left(12\,\frac{\rho_T}{\rho_W}\right)\left(4f_T\,\frac{L_T}{D_T} + K_{C,T} + K_{E,T}\right)\left(\frac{U_T^2}{2gc}\right)$	$\left(H_Z\right)_T + \left(H_U\right)_T$ $- \left(H_U\right)_K + \left(H_F\right)_T$
AB	Afterburner	$\left(12\,\frac{\rho_{AB}}{\rho_W}\right)\left(\frac{g}{gc}\,Z_{AB}\right)$	$\left(12\,\frac{\rho_{AB}}{\rho_W}\right)\left(\frac{U_{AB}^2}{2gc}\right)$	$\left(12\,\frac{\rho_{AB}}{\rho_W}\right)\left(4f_{AB}\,\frac{L_{AB}}{D_{AB}}\right)\left(\frac{U_{AB}^2}{2gc}\right)$	$\left(H_Z\right)_{AB} - \left(H_Z\right)_T + \left(H_U\right)_{AB}$ $- \left(H_U\right)_T + \left(H_F\right)_{AB}$
X	Afterburner Exhaust Duct	$\left(12\,\frac{\rho_X}{\rho_W}\right)\left(\frac{g}{gc}\,Z_X\right)$	$\left(12\,\frac{\rho_X}{\rho_W}\right)\left(\frac{U_X^2}{2gc}\right)$	$\left(12\,\frac{\rho_X}{\rho_W}\right)\left(4f_X\,\frac{L_X}{D_X} + K_{C,X}\right)\left(\frac{U_X^2}{2gc}\right)$	$\left(H_Z\right)_X - \left(H_Z\right)_{AB} + \left(H_U\right)_X$ $- \left(H_U\right)_{AB} + \left(H_F\right)_X$
V	Venturi Inlet Duct	$\left(12\,\frac{\rho_V}{\rho_W}\right)\left(\frac{g}{gc}\,Z_V\right)$	$\left(12\,\frac{\rho_V}{\rho_W}\quad\frac{U_V^2}{2gc}\right)$	$\left(12\,\frac{\rho_V}{\rho_W}\right)\left(4f_V\,\frac{L_V}{D_V} + K_{C,V} + K_B\right)\left(\frac{U_V^2}{2gc}\right)$	$\left(H_Z\right)_V - \left(H_Z\right)_V + \left(H_U\right)_V$ $- \left(H_U\right)_X + \left(H_F\right)_V$

Z_{AB} = 5.81 ft

Z_x = 6.66 ft

Z_v = 10.79 ft (midpoint)

L_i = nominal length, ft, from Table 12

D_i = hydraulic diameter, ft, from Table 12

f_i = friction factor = $0.00140 + 0.125/(N_{Re,i})^{0.32}$

$N_{Re,i}$ = Reynolds number, from Table 27

$K_{c,i}$ = contraction loss coefficient

$K_{c,T} = 0.75\ (1-S_T/S_K)$

$K_{c,x} = 0.75\ (1-S_x/S_{AB})$

$K_{E,T}$ = expansion loss coefficient = $(1-S_T/S_{AB})^2$

S_i = smallest cross-sectional area, ft^2, from Table 12

K_B = loss coefficient for 180°F U-Bend = 1.2

The empirical formulas for the friction factor f, for the contraction loss coefficient K_c, for the expansion loss coefficient K_E, and for the U-bend loss coefficient K_B, were taken from Perry(7).

Numerical values in thousands of inches of water for the elevation head H_Z, the velocity head H_U, the friction loss H_F, and the total head loss H_T, are listed in Table 29 for each item of equipment and for each experimental run. Values for the venturi inlet duct were not determined at this time because the gas temperatures were not directly measured in this duct.

From Table 29, the total head losses were less than 0.0004 inches of water in the rotary kiln, and less than 0.011 inches of water in the afterburner. In the more constricted sections of the system, the total head losses were somewhat higher: 0.012 to 0.040 inches of water in the kiln-to-afterburner transfer duct, and 0.059 to 0.171 inches of water in the afterburner exhaust duct.

Equilibria Among Chlorine Species

In the earlier discussion of combustion stoichiometry, the assumption was made that HCl was the dominant chlorine species at the range of conditions found in the kiln and in the afterburner.

TABLE 29. PROFILE OF SYSTEM HEADS

Inches of Water X 10^3

Test Date	Run	Rotary Kiln				Transfer Duct				Afterburner				Exhaust Duct			
		H_Z	H_U	H_F	H_T	H_Z	H_U	H_F	H_T	H_Z	H_U	H_F	H_T	H_Z	H_U	H_F	H_T
0817	1	0	0.16	0.01	0.17	8.7	7.1	8.7	24.3	17.7	2.4	0.3	4.6	21.8	65.5	48.6	114.9
0817	2	0	0.08	0.01	0.09	8.7	3.3	4.1	16.0	17.8	1.7	0.2	7.7	21.8	46.5	34.8	82.9
0819	1	0	0.04	0.00	0.04	9.3	1.5	1.9	12.7	19.2	1.2	0.1	9.7	24.0	32.2	24.2	59.5
0819	2	0	0.05	0.00	0.05	8.7	2.0	2.5	13.1	19.5	1.2	0.1	10.1	24.0	32.2	24.2	59.2
0823	1	0	0.05	0.00	0.05	9.6	2.2	2.7	14.4	19.2	1.4	0.1	8.9	24.0	37.2	27.9	68.0
0823	2	0	0.08	0.01	0.09	9.2	3.3	4.1	16.5	19.4	1.5	0.1	8.5	23.9	40.4	30.2	73.0
0825	1	0	0.20	0.02	0.22	8.0	8.7	10.7	27.2	16.4	2.7	0.3	2.7	20.2	73.5	54.6	128.1
0825	2	0	0.19	0.02	0.21	7.9	8.5	10.4	26.6	16.4	2.6	0.3	2.9	20.1	71.0	52.9	124.0
0901	1	0	0.16	0.01	0.17	8.0	7.1	8.7	23.6	16.8	2.5	0.3	4.5	20.6	65.7	49.0	115.1
0901	2	0	0.09	0.01	0.10	8.0	3.8	4.7	16.4	16.4	1.9	0.2	6.7	20.2	50.7	38.1	90.0
0906	1	0	0.14	0.01	0.15	7.9	6.1	7.5	21.4	16.7	2.3	0.2	5.2	20.5	62.5	46.7	109.8
0906	2	0	0.16	0.01	0.17	7.9	6.8	8.3	22.8	16.5	2.4	0.3	4.5	20.1	66.7	49.2	116.2
0908	1	0	0.18	0.01	0.19	7.9	7.7	9.5	24.9	16.6	2.5	0.3	3.8	20.3	69.3	51.6	121.1
0908	2	0	0.13	0.01	0.14	7.9	5.7	7.1	20.6	16.6	2.2	0.2	5.4	20.2	60.4	45.2	106.2
0913	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0913	2	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0922	1	0	0.33	0.02	0.35	7.9	14.4	17.7	39.7	17.0	3.6	0.3	-1.4	20.5	99.1	73.1	170.7
0922	2	0	0.22	0.02	0.24	7.9	9.5	11.7	28.9	16.7	2.9	0.3	2.5	20.3	80.2	59.5	139.3
0926	1	0	0.32	0.02	0.34	9.0	13.9	17.0	39.6	20.5	2.9	0.3	0.8	24.1	82.1	60.2	141.9
0926	2	0	0.26	0.02	0.28	7.8	11.3	13.9	32.7	17.0	3.1	0.3	1.3	20.4	85.5	63.3	147.9

In addition to the assumed combustion reactions for trichlorobenzene and for hexachlorobenzene, forming HCl, two additional reactions to consider are the equilibria between HCl and Cl_2 and between Cl_2 and $Cl\cdot$:

(E) $2HCl + \frac{1}{2} O_2 \rightleftharpoons Cl_2 + H_2O$

(F) $Cl_2 \rightleftharpoons 2\ Cl\cdot$

For these reactions, the Gibbs free energy change is evaluated from the free energies of formation at temperature θ:

$$(\Delta F_R^\theta)_E = (\Delta F_f^\theta)_{Cl_2} + (\Delta F_f^\theta)_{H_2O} - 2(\Delta F_f^\theta)_{HCl} - \frac{1}{2}(\Delta F_f^\theta)_{O_2}$$

$$(\Delta F_R^\theta)_F = 2(\Delta F_f^\theta)_{Cl\cdot} - (\Delta F_f^\theta)_{Cl_2}$$

Using the JANAF values$^{(8)}$ for ΔF_f^θ in Table 30, and since $(\Delta F_f^\theta)_{Cl_2} = (\Delta F_f^\theta)_{O_2} = 0$, the calculated values for $(\Delta F_R^\theta)_E$ and $(\Delta F_R^\theta)_F$ are listed in Table 30. Also listed are the logarithms of the corresponding equilibrium constants:

$$\log_{10}(K_{eq}^\theta)_E = -\ 0.43429\ (\Delta F_R^\theta)_E/RT$$

$$\log_{10}(K_{eq}^\theta)_F = -\ 0.43429\ (\Delta F_R^\theta)_F/RT$$

where $R = 1.9872 \times 10^{-3}$ kcal/gmole, °K

Figure 14 graphically shows the temperature variation of the equilibrium constants. At higher temperatures, both HCl and atomic $Cl\cdot$ become increasingly favored, at the expense of molecular Cl_2.

Assume a combustion gas mixture has a total flowrate of N_T^O lb moles per hour with only HCl being considered as a chlorine-containing constituent (as in Table 24), and assume the corresponding constituent flowrates in lb moles per hour are N_{HCl}^O, $N_{H_2O}^O$, and $N_{O_2}^O$. Then if Reaction E proceeds such that 2X lb moles per hour of HCl disappear, and if Reaction F proceeds such that 2Y lb moles per hour of $Cl\cdot$ appear, then the equilibrium mole fractions are:

TABLE 30. THERMODYNAMICS OF CHLORINE SPECIES

Temperature		Free Energy of Formation ΔF_f^θ, kcal/gram mole			Free Energy of Reaction ΔF_R^θ, kcal/g mole		Log of Equilibrium Constant $\log_{10}(K_{eq}^\theta)$	
°K	°F	$H_2O(g)$	HCl(g)	Cl•(g)	Reaction E	Reaction F	Reaction E	Reaction F
298	77	-54.636	-22.778	25.102	-9.080	50.204	6.659	-36.818
300	80	-54.617	-22.782	25.079	-9.053	50.158	6.595	-36.539
400	260	-53.519	-23.012	23.779	-7.495	47.558	4.095	-25.984
500	440	-52.361	-23.224	22.451	-5.913	44.902	2.584	-19.626
600	620	-51.156	-23.420	21.100	-4.316	42.200	1.572	-15.371
700	800	-49.915	-23.602	19.731	-2.711	39.462	0.846	-12.320
800	980	-48.646	-23.774	18.347	-1.098	36.694	0.300	-10.024
900	1160	-47.352	-23.936	16.952	0.520	33.904	-0.126	- 8.233
1000	1340	-46.040	-24.093	15.547	2.146	31.094	-0.469	- 6.795
1100	1520	-44.712	-24.243	14.133	3.774	28.266	-0.750	- 5.616
1200	1700	-43.371	-24.390	12.713	5.409	25.426	-0.985	- 4.630
1300	1880	-42.022	-24.534	11.286	7.046	22.572	-1.184	- 3.794
1400	2060	-40.663	-24.675	9.853	8.687	19.706	-1.356	- 3.076
1500	2240	-39.297	-24.813	8.416	10.329	16.832	-1.505	- 2.452
1600	2420	-37.927	-24.950	6.975	11.973	13.950	-1.636	- 1.905
1700	2600	-36.549	-25.086	5.530	13.623	11.060	-1.751	- 1.422
1800	2780	-35.170	-25.221	4.080	15.272	8.160	-1.854	- 0.991
1900	2960	-33.786	-25.353	2.629	16.920	5.258	-1.946	- 0.605
2000	3140	-32.401	-25.486	1.174	18.571	2.348	-2.029	- 0.257

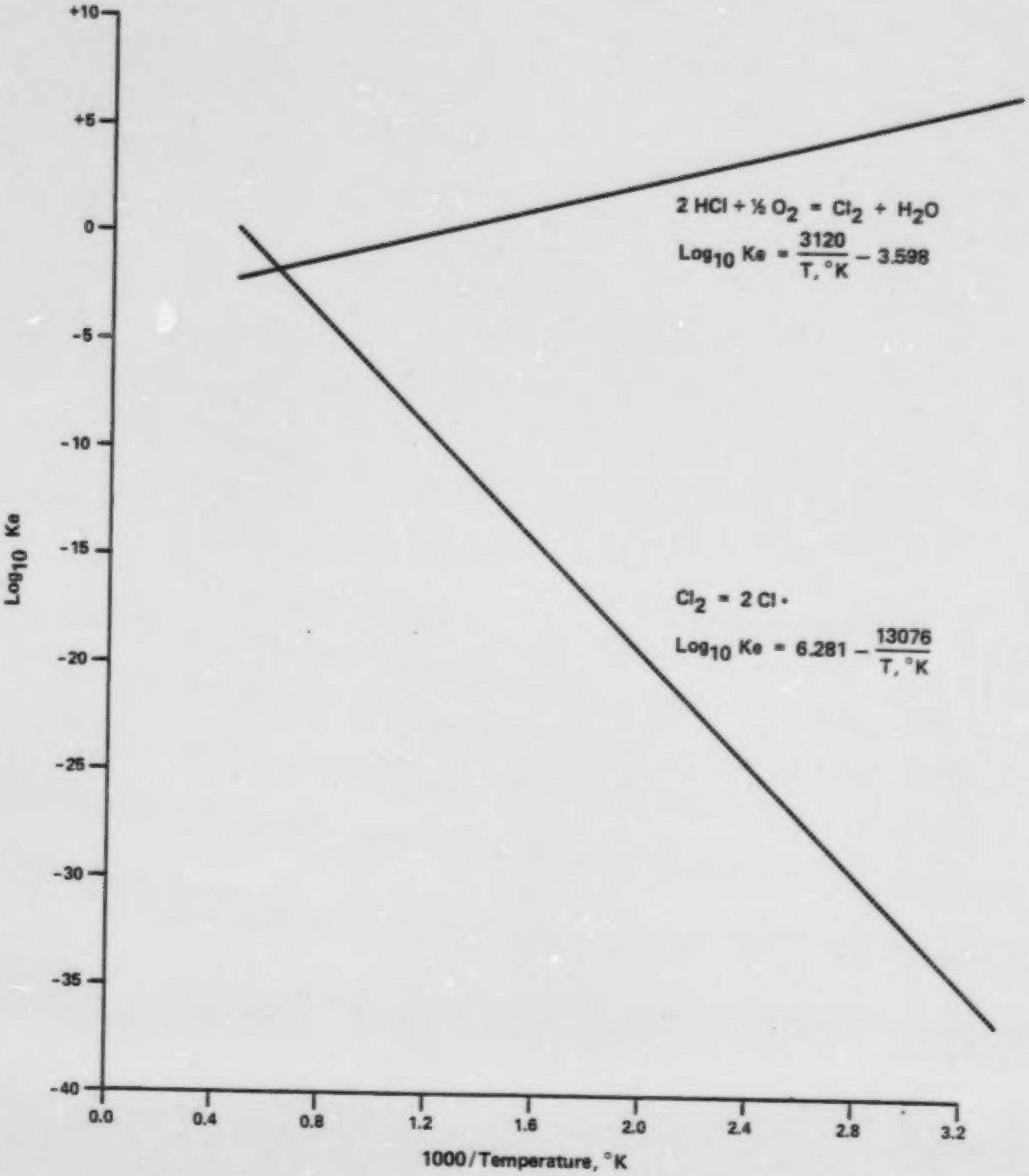


FIGURE 14
EQUILIBRIUM CONSTANTS FOR CHLORINE REACTIONS

$$[HCl] = (N_{HCl}^{o} - 2X)/N_T$$

$$[O_2] = (N_{O_2}^{o} - \tfrac{1}{2}X)/N_T$$

$$[H_2O] = (N_{H_2O}^{o} + X)/N_T$$

$$[Cl_2] = (X - Y)/N_T$$

$$[Cl\bullet] = 2Y/N_T$$

$$N_T = N_T^{o} - \frac{1}{2}X + Y$$

Then (L) $$(K_{eq})_E = \frac{[Cl_2][H_2O]}{[HCl]^2[O_2]^{1/2}} = \frac{(X-Y)(N_{H_2O}^{o} + X)(N_T^{o} - \frac{1}{2}X + Y)^{1/2}}{(N_{HCl}^{o} - 2X)^2(N_{O_2}^{o} - \frac{1}{2}X)^{1/2}}$$

(M) $$(K_{eq})_F = \frac{[Cl\bullet]^2}{[Cl_2]} = \frac{(2Y)^2}{(X-Y)(N_T^{o} - \frac{1}{2}X + Y)}$$

If N_{HCl}^{o} is much smaller than $N_{H_2O}^{o}$, $N_{O_2}^{o}$, and N_T^{o} (the case for the runs listed in Table 24), then $N_T \quad N_T^{o}$, $N_{H_2O} \quad N_{H_2O}^{o}$, and $N_{O_2} \quad N_{O_2}^{o}$, and Equations (L) and (M) may be simplified:

(N) $$Y = \frac{(N_{HCl}^{o} - 2X)}{2}\left[\frac{(N_{O_2}^{o})^{1/2}(N_T^{o})^{1/2}(K_{eq})_E(K_{eq})_F}{N_{H_2O}^{o}}\right]^{1/2}$$

(O) $$X = \frac{4Y^2}{(N_T^{o})(K_{eq})_F} + Y$$

For each run, the temperature in the kiln (θ_K) or in the afterburner (θ_{AB}) is known from Table 20, the corresponding values of $(K_{eq})_E$ and $(K_{eq})_F$ can be determined from Figure 14, and the values of N_{HCl}^{o}, $N_{H_2O}^{o}$, and $N_{O_2}^{o}$ are obtained from Table 24. Either Equations (L) and (M), or alternatively Equations (N) and (O), may then be solved for X and Y by an iterative procedure. The initial value of X=0 might be used in Equation (N) to start the procedure.

Table 31 summarizes these calculations for the runs (0819-1, 0819-2, 0901-1, 0901-2, 0906-1, 0906-2, 0908-1, and 0908-2) where chlorobenzenes were incinerated.

For all the runs, HCl accounts for greater than 99.8 per cent of all the chlorine under the conditions in the rotary kiln. Under the higher-temperature conditions in the afterburner, HCl accounts for greater than 98.8 per cent of all the chlorine. These results substantiate the assumption previously made, and validate the material balances of Table 24.

Almost all of the chlorine not present as HCl is in the form of the free-radical Cl• rather than as molecular chlorine.

ANALYSIS OF PROCESS THERMAL DATA

Heat Input to the Incinerator System

The heat input rate for each of the runs is listed in Table 32, for the rotary kiln and for the afterburner. The feed rates of propane, air, toluene, TCB, and HCB were taken from Table 24. The average temperatures for each run for the propane feed and for the air feed were calculated from the data for discrete times in Table 19.*

The sensible heat for the propane feed, (ΔHs) propane, was calculated above a baseline temperature of 77°F(25°C). The heat capacity of propane is:(9)

		C_p, Btu/lb mole °F	
T, °F	T, °F	Experimental	Calculated
298	77	17.57	17.68
500	440	27.02	27.12
700	800	34.20	34.65
1000	1340	41.83	42.54

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*For the purpose of this analysis, the temperature of air leaking into the rotary kiln was assumed the same as the measured air fed to the kiln burner.

TABLE 31. CALCULATED QUANTITIES OF CHLORINE SPECIES

Test Date Run	0819 1	0819 2	0901 1	0901 2	0906 1	0906 2	0908 1	0908 2	0819 1	0819 2	0901 1	0901 2	0906 1	0906 2	0908 1	0908 2
θ, Temperature, °F	1304	1420	1600	1599	1591	1600	1599	1600	1786	1765	2115	2162	2128	2158	2148	2152
$\log_{10} (K_{eq})_E$	-0.414	-0.610	-0.871	-0.870	-0.859	-0.871	-0.870	-0.871	-1.097	-1.074	-1.417	-1.456	-1.428	-1.453	-1.444	-1.448
$\log_{10} (K_{eq})_F$	-7.065	-6.240	-5.146	-5.152	-5.196	-5.146	-5.152	-5.146	-4.200	-4.298	-2.860	-2.697	-2.815	-2.710	-2.745	-2.731
$(K_{eq})_E$	0.3858	0.2453	0.1344	0.1349	0.1382	0.1344	0.1349	0.1344	0.0799	0.0844	0.0383	0.0350	0.0373	0.0353	0.0359	0.0357
$(K_{eq})_F$	8.62E-8	5.75E-7	7.14E-6	7.05E-6	6.36E-6	7.14E-6	7.05E-6	7.14E-6	6.31E-5	5.03E-5	0.00138	0.00201	0.00153	0.00195	0.00180	0.00186
$N^{0}_{O_2}$, lb moles/hr	1.680	2.200	3.173	3.034	1.935	3.741	3.714	3.371	6.378	6.894	5.767	5.443	4.652	6.598	6.230	6.429
$N^{0}_{H_2O}$, lb moles/hr	3.361	3.495	6.546	4.432	7.122	6.275	6.753	5.645	10.453	9.892	15.256	13.228	15.867	14.838	15.313	13.715
N^{0}_{HCl}, lb moles/hr X10^{3}	4.644	4.644	9.114	3.645	18.225	18.225	36.450	36.450	4.644	4.644	9.114	3.645	18.225	18.225	36.450	36.450
N^{0}_{T}, lb moles/hr	26.764	29.792	53.134	38.771	49.633	52.108	55.695	48.002	85.916	85.708	113.742	90.779	110.731	112.490	115.672	107.605
X, lb moles/hr X 10^{6}	1.22	1.74	6.70	2.89	11.3	15.2	32.8	35.2	7.85	7.55	43.0	20.3	82.5	102.6	194.7	206.5
Y, lb moles/hr X 10^{6}	0.60	1.33	6.28	2.78	10.0	13.3	25.9	26.8	7.78	7.48	42.5	20.0	81.6	101.3	191.9	203.3
N_{Cl_2}, lb moles/hr X 10^{6}	0.62	0.41	0.43	0.12	1.29	1.93	6.90	8.44	0.071	0.077	0.45	0.23	0.91	1.35	2.80	3.18
$N_{Cl\bullet}$, lb moles/hr X 10^{6}	1.20	2.65	12.56	5.55	20.0	26.6	51.8	53.5	15.6	14.9	85.0	40.0	163.2	202.6	383.8	406.7
N_{HCl}/N^{0}_{HCl}	0.9995	0.9993	0.9985	0.9984	0.9987	0.9984	0.9982	0.9981	0.9966	0.9967	0.9906	0.9889	0.9909	0.9887	0.9893	0.9887

TABLE 32. HEAT BALANCE CALCULATIONS

	Test Date Run		0817 1	0817 2	0819 1	0819 2	0823 1	0823 2	0825 1	0825 2	0901 1	0901 2	0906 1	0906 2	0908 1	0908 2	0913 1	0913 2	0922 1	0922 2	0926 1	0926 2
Rotary Kiln	Feed Rates lb moles/hr	Propane	1.329	0.852	0.597	0.616	0.611	0.620	1.714	1.404	1.169	0.802	1.420	1.178	1.331	1.104	1.730	1.562	1.709	1.522	1.719	1.772
		Air	53.42	36.36	25.45	28.44	31.15	37.78	55.90	55.38	50.50	37.05	46.67	49.63	52.91	45.67	—	—	72.49	58.60	75.88	63.53
		Toluene $x10^3$	0	58.84	57.50	57.50	58.84	58.84	58.84	58.84	143.53	57.41	51.71	51.71	44.58	44.58	0	0	0	0	0	0
		TCB x 10^3	0	0	0	0	0	0	0	0	3.038	1.215	6.075	6.075	12.150	12.150	50.156	50.156	0	0	0	0
		HCB x 10^3	0	0	0.774	0.774	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Temps, °F	Propane	110	124	107	121	107	124	123	141	111	123	112	128	124	139	109	124	101	114	91	112
		Air	86	89	88	89	91	95	118	132	85	89	88	93	95	99	84	90	72	77	78	87
	Sensible Heats, 10^3 Btu/hr	Propane	0.804	0.740	0.328	0.500	0.335	0.530	1.456	1.679	0.729	0.601	0.912	1.113	1.156	1.277	1.014	1.356	0.749	1.034	0.440	1.138
		Air	3.400	3.068	1.973	2.400	3.056	4.745	15.872	21.077	2.875	3.126	3.618	5.552	6.646	6.992	—	—	-2.334	0.121	0.676	4.489
	Heats of Combustion, 10^3 Btu/hr	Propane	1168.6	749.2	525.0	541.7	537.3	545.2	1507.2	1234.6	1027.9	705.2	1055.2	1035.8	1170.4	970.8	1521.2	1373.5	1502.8	1338.3	1511.6	1558.2
		Toluene	0	95.48	93.30	93.30	95.48	95.48	95.48	95.48	232.90	93.16	83.91	83.91	72.34	72.34	0	0	0	0	0	0
		TCB	0	0	0	0	0	0	0	0	3.385	1.354	6.770	6.770	13.539	13.539	55.891	55.891	0	0	0	0
		HCB	0	0	0.927	0.927	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total Heat Input, 10^3 Btu/hr		1172.8	848.5	621.5	638.8	636.2	646.0	1620.0	1352.8	1267.8	803.5	1150.4	1133.1	1264.1	1065.0	—	—	1501.2	1339.5	1512.7	1563.8
	Gas Flow, lb moles/hr		56.083	38.185	26.764	29.792	32.487	39.142	59.445	58.305	53.134	38.771	49.633	52.108	55.695	48.002	—	—	75.909	61.648	79.321	67.078
	Gas Temp., °F		1404	1410	1304	1420	1238	1323	1579	1600	1600	1599	1591	1600	1599	1600	1615	1618	1605	1611	1363	1621
	Output Enthalpy	10^3 Btu/hr	584.2	400.9	257.6	314.8	293.8	376.8	718.6	708.3	647.0	468.2	605.0	631.3	675.3	581.6	—	—	915.9	750.3	793.7	826.4
		10^3 Btu/lb mole	10.417	10.498	9.624	10.565	9.045	9.626	12.089	12.148	12.176	12.076	12.190	12.115	12.125	12.117	—	—	12.065	12.171	10.006	12.320
	Heat Loss	10^3 Btu/hr	588.6	447.6	363.9	324.0	342.4	269.2	901.4	644.5	620.8	335.3	545.4	501.8	588.8	483.4	—	—	585.3	589.2	719.1	737.4
		Pct. of Input	50.19	52.76	58.56	50.73	53.81	41.68	55.64	47.64	48.97	41.73	47.41	44.29	46.58	45.39	—	—	38.99	43.99	47.53	47.15
Transfer Duct and Upstream Half of Afterburner	Feed Rates, lb moles/hr	Propane	1.522	1.419	1.360	1.244	1.415	1.310	1.797	1.723	1.812	1.821	1.806	1.752	1.807	1.694	1.776	1.738	1.785	1.733	1.359	1.877
		Air	57.80	57.54	56.43	53.51	56.68	54.09	56.53	55.25	56.98	56.37	57.49	56.90	56.37	56.22	57.72	57.07	59.37	58.84	55.00	58.04
	Temps, °F	Propane	115	136	101	111	101	115	125	132	104	111	106	118	116	129	104	116	96	107	90	107
		Air	86	89	88	89	91	95	108	132	89	93	89	96	99	106	89	94	77	83	80	90
	Sensible Heats, 10^3 Btu/hr	Propane	1.063	1.559	0.596	0.776	0.620	0.915	1.595	1.760	0.894	1.135	0.958	1.322	1.296	1.633	0.876	1.246	0.619	0.951	0.323	1.030
		Air	3.607	4.855	4.374	4.515	5.561	6.794	12.156	21.027	4.808	6.306	4.851	7.538	8.630	11.315	4.871	6.776	0.122	2.542	1.244	5.296
	Propane Hc, 10^3 Btu/hr		1338.3	1247.8	1195.9	1093.9	1244.2	1151.9	1580.1	1515.1	1593.3	1601.2	1588.1	1540.6	1588.9	1489.6	1561.7	1528.3	1569.6	1523.9	1195.0	1650.5
	Total Heat Input, 10^3 Btu/hr		1343.1	1254.2	1200.9	1099.2	1250.4	1159.6	1593.9	1537.9	1599.0	1608.7	1593.9	1549.5	1598.8	1502.6	1567.5	1536.3	1570.3	1527.4	1196.6	1656.8
	Total Input Enth., 10^3 Btu/hr		1927.3	1655.1	1458.5	1414.0	1544.2	1536.4	2312.5	2246.2	2246.0	2076.9	2198.9	2180.8	2274.1	2084.2	—	—	2486.2	2277.7	1990.3	2483.2
	Gas Flow, lb moles/hr		116.930	98.558	85.916	85.788	92.002	95.854	119.572	116.996	113.742	98.779	110.731	112.490	115.672	107.606	—	—	138.852	123.953	137.034	128.868
	Gas Temp., °F		1974	1967	1786	1765	1790	1773	2156	2162	2115	2162	21.28	2158	2148	2152	2097	2139	2000	2135	1655	2088
	Output Enthalpy	10^3 Btu/hr	1800.6	1510.4	1179.2	1158.6	1269.2	1295.7	2063.7	2012.7	1911.9	1699.4	1880.8	1928.4	1975.4	1836.9	—	—	2275.0	2088.0	1714.0	2129.7
		10^3 Btu/lb mole	15.399	15.325	13.725	13.505	13.795	13.517	17.259	17.203	16.809	17.204	16.985	17.143	17.078	17.070	—	—	16.384	16.845	12.508	16.526
	Heat Loss	10^3 Btu/hr	126.7	144.7	279.3	255.4	275.0	240.8	248.8	233.5	334.1	377.5	318.1	252.4	298.7	247.4	—	—	211.2	189.7	276.3	353.5
		Pct. of Input	6.57	8.74	19.15	18.06	17.81	15.67	10.76	10.40	14.88	18.18	14.47	11.57	13.13	11.87	—	—	8.50	8.33	13.88	14.24
Downstream Half of Afterburner and Upstream Half of Exhaust Duct	Gas temp, °F		1810	1810	1609	1610	1611	1619	1983	2000	1949	1997	1961	2000	1986	2000	1966	2000	1964	1999	1600	1974
	Output Enthalpy	10^3 Btu/hr	1630.6	1373.4	1046.7	1043.1	1119.6	1168.0	1875.2	1841.1	1741.2	1551.8	1712.7	1767.8	1805.9	1689.4	—	—	2121.4	1936.7	1649.3	1997.3
		10^3 Btu/lb mole	13.945	13.935	12.182	12.160	12.169	12.185	15.683	15.737	15.308	15.710	15.467	15.715	15.613	15.700	—	—	15.278	15.625	12.035	15.499
	Heat Loss	10^3 Btu/hr	170.0	137.0	132.5	115.5	149.6	127.7	188.5	171.6	170.7	147.6	168.1	160.6	169.5	147.5	—	—	153.6	151.3	64.7	132.4
		Pct. of Input	9.44	9.07	11.24	9.97	11.79	9.85	9.13	8.52	8.93	8.68	8.94	8.33	8.58	8.03	—	—	6.75	7.24	3.78	6.22
Total System to Midpoint of Exhaust Duct	Total Heat Input, 10^3 Btu/hr		2515.9	2102.7	1822.4	1738.0	1886.6	1805.6	3213.9	2890.7	2866.8	2412.2	2744.3	2682.6	2862.9	2567.6	—	—	3071.5	2866.9	2709.3	3220.6
	Total Heat Loss	10^3 Btu/hr	885.3	729.3	775.7	694.9	767.0	637.6	1338.7	1049.6	1125.6	860.4	1031.6	914.8	1057.0	878.2	—	—	950.1	930.2	1060.0	1223.3
		Pct. of Input	35.19	34.68	42.56	39.98	40.66	35.31	41.65	36.31	39.26	35.67	37.59	34.10	36.92	34.20	—	—	30.93	32.45	39.12	37.98

By the method of Anderson, Beyer, and Watson, using group contributions, (C_p) propane $= 0.41 + 64.71 \times 10^{-3}T - 22.58 \times 10^{-6}T^2$ for propane, where T is the temperature in °K. The calculated values are listed above along with the experimental values.

For air,$^{(10)}$

$$(C_p)_{air} = 6.27 + 2.09 \times 10^{-3}T - 0.459 \times 10^{-6}T^2$$

where T is in °K and where $(C_p)_{air}$ is in Btu/lb mole °F or cal/g mole °K.

In general, if $C_p = A + BT + CT^2$, the enthalpy of a gas ΔH^T in Btu/lb mole at temperature T °K is

$$\Delta H^T = 1.8 \int_{T_o}^{T} C_p dT = 1.8 \int_{T_o}^{T} (A + BT + CT^2)\, dT$$

$$\text{(P)} \quad \Delta H^T = 1.8\left(AT + \frac{B}{2}T^2 + \frac{C}{3}T^3\right) - I_o$$

where I_o is an integration constant,

$$I_o = A\,T_o + \frac{B}{2}T_o^{\,2} + \frac{C}{3}T_o^{\,3}.$$

If ΔH^{298} is defined as zero at $T_o = 298$ °K, then

$(I_o)_{propane} = 5{,}033.3$ Btu/lb mole
$(I_o)_{air} = 3{,}523.0$ Btu/lb mole

The sensible heat for each run, for the feed to the kiln and to the afterburner, is listed in Table 32, as calculated by:

$$\Delta H^T_{Propane} = M_{Propane}\,(0.74T + 5.8239 \times 10^{-2}T^2 - 13.549 \times 10^{-6}T^3 - 5033.3)$$

$$\Delta H^T_{Air} = M_{Air}\,(11.29T + 0.1881 \times 10^{-2}T^2 - 0.275 \times 10^{-6}T^3 - 3523.0)$$

where ΔH_T is in Btu/hr
M is in lb moles/hr
T is in °K

The heat of combustions were calculated from heats of formation, using the following values, the stoichiometry of Equations A,B,C, and D, and with the combustion products all in the gaseous state at 298°K:

	Reference	ΔHf kcal/g mole	ΔHc kcal/g mole	ΔHc Btu/lb mole
Propane	(1)	- 24.820	- 488.513	- 879,320
Toluene	(1)	+ 11.920	- 901.487	- 1,622,680
1,2,4-Trichlorobenzene (TCB)	(2)	- 11.410	- 619.085	- 1,114,350
Hexachlorobenzene (HCB)	(2)	- 31.312	- 665.372	- 1,197,670

(1) Weast, R.C. (ed), Handbook of Chemistry and Physics, 58th ed., CRC Press, Cleveland, 1977, pp. D-82, D-83.

(2) Kirk-Othmer Encyclopedia of Chemical Technology, 3rd Edition, Vol 5, 1979, p. 799.

Table 32 lists the total heat input to the kiln and to the afterburner for each run. These values are the sums of the sensible heats for propane and air and the heats of combustion of propane and liquid organic materials.

Enthalpy of Combustion Gases

Table 24 lists the flowrates for each constituent in the combustion gases, for the kiln and for the afterburner. For the individual constituents, the heat capacity coefficients in $C_p = A+BT+CT^2$ (where T is in degrees K and C_p is in cal/g mole, °K) are:(10)

	A	$B \times 10^3$	$C \times 10^6$
CO_2	6.85	8.533	-2.475
O_2	6.13	2.99	-0.806
N_2	6.30	1.819	-0.345
HCl	6.64	0.959	-0.057
H_2O	6.89	3.283	-0.343

Following the discussion for the feed propane and air in the previous section, the enthalpy (baseline 298°K) for each constituent k at a temperature T °K may be evaluated according to equation (P),

$$(\Delta H^T)_k = 1.8\ (AT + \frac{B}{2}T^2 + \frac{C}{3}T^3) - I_o.$$

The total enthalpy of the combustion gas stream is then calculated as:

$$\begin{aligned}\Delta H^T_{Total} = {} & M_{CO_2}\ (12.330T + 7.6797\text{x}10^{-3}T^2 - 1.4850\text{x}10^{-6}T^3 - 4317.0)\\ & + M_{O_2}\ (11.034T + 2.6910\text{x}10^{-3}T^2 - 0.4836\text{x}10^{-6}T^3 - 3514.3)\\ & + M_{N_2}\ (11.340T + 1.6371\text{x}10^{-3}T^2 - 0.2070\text{x}10^{-6}T^3 - 3519.2)\\ & + M_{HCl}\ (11.952T + 0.8631\text{x}10^{-3}T^2 - 0.0342\text{x}10^{-6}T^3 - 3637.4)\\ & + M_{H_2O}\ (12.402T + 2.9547\text{x}10^{-3}T^2 - 0.2058\text{x}10^{-6}T^3 - 3952.7)\end{aligned}$$

where ΔH^T_{Total} = Total output enthalpy, Btu/hr

T = gas temperature, °K

M_k = flowrate of constituent k, lb moles/hr

Table 32 lists the enthalpies for the kiln combustion gas, for the combustion gas at the midpoint of the afterburner, and for the gas at the midpoint of the afterburner exhaust duct (using the same values for M_k as for the afterburner combustion gas). The locations are where the gas temperatures are measured.

Heat Losses from the Combustion Gases

The heat losses from the combustion gases were calculated by difference, between the input enthalpy to each portion of the system and the enthalpy of the combustion gases in that portion. Table 32 lists these losses both in Btu per hour and as a percentage of the total input enthalpy. The averages for all runs are listed in Table 33. Almost half of the heat input to the rotary kiln is lost, while the heat losses to both halves of the afterburner together amount to about one-fourth of the total input enthalpy. For the entire system to the midpoint of the afterburner exhaust duct, the average heat losses are about 37 per cent of the total system heat input.

TABLE 33. AVERAGE HEAT LOSSES

Portion of System	Internal Surface Area, Square Feet	Average Heat Losses		
		Pct of Input Enthalpy	Btu/hr	Btu/ft^2, hr
Rotary Kiln	115.492	47.95	532,700	4,612
Transfer Duct and Upstream Half of Afterburner	73.265	13.12	259,100	3,536
Downstream Half of Afterburner and Upstream Half of Exhaust Duct	70.626	8.58	147,700	2,091
Total System to Midpoint of Exhaust Duct	259.383	36.92	939,400	3,622

Also in Table 33 are the internal surface areas for the respective portions of the system, derived from Table 12. The heat flux in Btu/ft^2, hr is listed, showing values of about 4,600 Btu/ft^2, hr for the kiln; of about 3,500 Btu/ft^2, hr for the transfer duct and upstream half of the afterburner; and of about 2,100 Btu/ft^2, hr for the downstream half of the afterburner plus the upstream half of the exhaust duct.

A system heat transfer analysis will be conducted to correlate these heat losses with experimental conditions. The steps planned for this analysis are in Appendix A to this report.

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SECTION 3

POHC/PIC MEASUREMENTS AND DRE VALUES

INTRODUCTION

The chlorinated benzene test series described generally in Section 1 not only served to complete the engineering shakedown of the CRF rotary kiln system and support subsystems and to provide the engineering data presented in Section 2, but the tests also produced much information on the behavior of HCB and 1,2,4-TCB at high temperatures. This section describes the procedures used to determine emission rates and DRE values for the two POHCs and to identify PICs.

A number of the sampling runs in the test series were used for purposes other than determination of DREs and PICs, such as the failure mode tests, evaluation of sampling techniques, etc.; these tests are described in detail in later sections of the report. Procedures for POHC feed control, sampling and analysis for these tests were similar to those described herein for the typical DRE runs.

In early experiments using HCB as the surrogate POHC, several trains were spiked with a variety of compounds (every HCB train was spiked with pentachlorobenzene) to determine both the efficiency with which the train retained the spikes and the analytical recovery to be expected. The results of these spike and recovery experiments were, for the most part, quite disappointing, showing that the conventional liquid impinger Method Five train was not well adapted even for stack sampling (temperature of 81°C) and would surely not suffice for hot zone sampling at the kiln and/or the afterburner transfer ducts. These limitations lead to the adopting of the Modified Method Five (MM5) train using the Battelle sampler with XAD-2 resin as the sorption medium. In this case, spike and recovery data were quite acceptable even for hot zone sampling at temperatures as high as 1150°C (2100°F).

The carrier (solvent) used throughout these experiments was toluene which was purchased in 18.93 l (5gal) cans. For safety considerations the solutions to be used in these experiments were made up in the toluene cans by removing a sufficient quantity of the toluene and then adding the required amount of the POHC (HCB or TCB) for the required final solution concentration. Further, since the solution feed rate of 2.84 l/hr had been determined previously (on the basis that the feed should not contribute more than 20% of the total heat release within the kiln in order to better control the exhaust temperature; the turndown ratio of the presently available burner is only about 3) this arrangement would allow feed for nearly 7 hours when these cans were used as the feed vessel. The can was fitted with an air inlet (fitted with an activated carbon filter) and a second pipe which terminated at the bottom of the can. This second pipe was connected to the positive displacement feed pump. A portion of the solution withdrawn could be recycled to the can to assure uniformity in the feed. The output of the feed pump was conducted to the feed lance through stainless tubing. The water cooled feed lance was located at the kiln front face (feed counter current to the rear mounted burner) so that the feed dripped from the lance to the hot surface of the kiln refractory. No attempt was made to atomize or distribute the feed material.

SAMPLING

Sampling was conducted for both combustion gases and for residual organics (POHC and possible PICs). In the former case, continuous samples of the combustion gases were withdrawn from the stack for the analyses of residual O_2, CO_2 and CO. In addition, provisions were made to allow analyses of these same combustion gases at such points as at the feed face of the kiln, in the kiln (exhaust) transfer duct and in the afterburner (exhaust) transfer duct. Continuous hard copy records of these measurements were made for each monitored zone. Propane flow to each of the burners was monitored using gas temperature corrected Validyne in-line monitors again producing hard copy of the gas flow on a continuous basis.

Since mass and energy balance as well as emission rate of the POHC (and/or any PICs) depends on a knowledge of the gas flowrate, provisions were made to measure this flow at each sampling point. Although pitot measurements with a suitably calibrated pitot tube are often used for gas flow rates, the nature of the gases and the flow conditions within the sampled hot zones were such that pitot measurements were not appropriate, and an alternate method had to be used. The method adopted was that of helium dilution using the relationship

$$C_{He} = \frac{q_{He}}{q_{He} + Q} \qquad (1)$$

where C_{He} is the helium concentration at the sampled point, q_{He} is the (constant) rate of helium injection and Q is the combustion gas flow at the sampled point. In order to utilize Equation (1), the point of injection of the helium must be sufficiently removed from the sampled point as to ensure complete mixing. The helium dilution system is described in more detail in Section 5.

In addition to the parameters discussed above, a number of attempts have been made at the CRF to measure both elemental chlorine and HCl with minimal success. The origin of this problem appears to be in the fact that heated sampling lines of more than 6 meters (20 ft) were required to conduct the sampled gas to the analytical system. These very lines appeared to have an avid affinity for the various inorganic forms of chlorine (as well as organic chlorine - a matter to be treated below). As a result, efforts were made to utilize a non-centralized analytical system and very short sampling lines. Further, a model of the scrubber system has been prepared which allows a correction to be made for the increasing Cl^- concentration resulting from the evaporation of Cl-containing make up water. Using this model and specific ion electrode measurements one can determine the rate of removal of HCl from the combustion gases. Preliminary results have been promising and are reported in Section 6 of this report.

The determination of the residual concentration of organics in the combustion gases was one of the primary objectives of the test series. As has been previously reported, sampling points have been established within both the kiln and afterburner exit ducts as well as in the stack. In the earlier experiments on HCB, sampling was only carried out at the stack since efforts to utilize the liquid impinger Method 5 at the hot zones resulted in very poor recovery of spikes (presumably due to evaporative losses of the organic impinger fluid). In the course of the remaining experiments, sampling at both the kiln and afterburner exit ducts was accomplished using the Modified Method Five (MM5) with the train consisting of a cooled Battelle sampler, using XAD-2 resin as the collection medium, followed by a water collecting impinger and a dryer preceding the gas flow measuring and control equipment. The MM5 train is shown in Figure 15. Measured spike and recovery data for both the standard Method Five and the Modified Method Five train will be presented in Section 7.

In several of the failure mode experiments in the kiln, considerable quantities of soot were produced. In order to attain better control over the sampling system, an in-line glass filter section was introduced upstream of the Battelle sampler. The filter and sampling line washings with 1:1 methylene chloride/acetone were considered to be a part of the sample.

The sample probe was 0.953 cm (0.375 in) stainless tube projecting some 25 cm (10 in) into the hot ducts. A schematic is shown in Figure 16. No attempt has been made to collect particulates from these hot zones since the flow conditions were such as to preclude iso-kinetic sampling in any case (this matter is more fully discussed below). The orifice end of the sampling tube is cut at a 45° angle with opening facing down stream. Further, as the temperature of the gas (and presumably of the entrained particles within the gas) was always far above the boiling points of the compounds for which sampling was conducted, it was thought reasonable that these compounds would indeed be in the vapor state. (This matter is treated further in Section 6.)

The hot gas sample, on being extracted from the sampled zone, was conducted through an air cooled 0.635 cm (0.25 in) stainless line of the order of 1.5 M (5 ft) in length. This particular length was chosen in order that by the time that the sample had traversed this distance its residual temperature was of the order of 121°C (250°F) or less. This was found to be the upper temperature for which the available water cooler could keep the Battelle sampler within the proper temperature range. As suggested above it was originally planned to use heat-traced sampling lines for the transfer of the gas from sampling port to the sampler. It was found that these lines were especially effective in retaining organics and thus had to be rinsed after

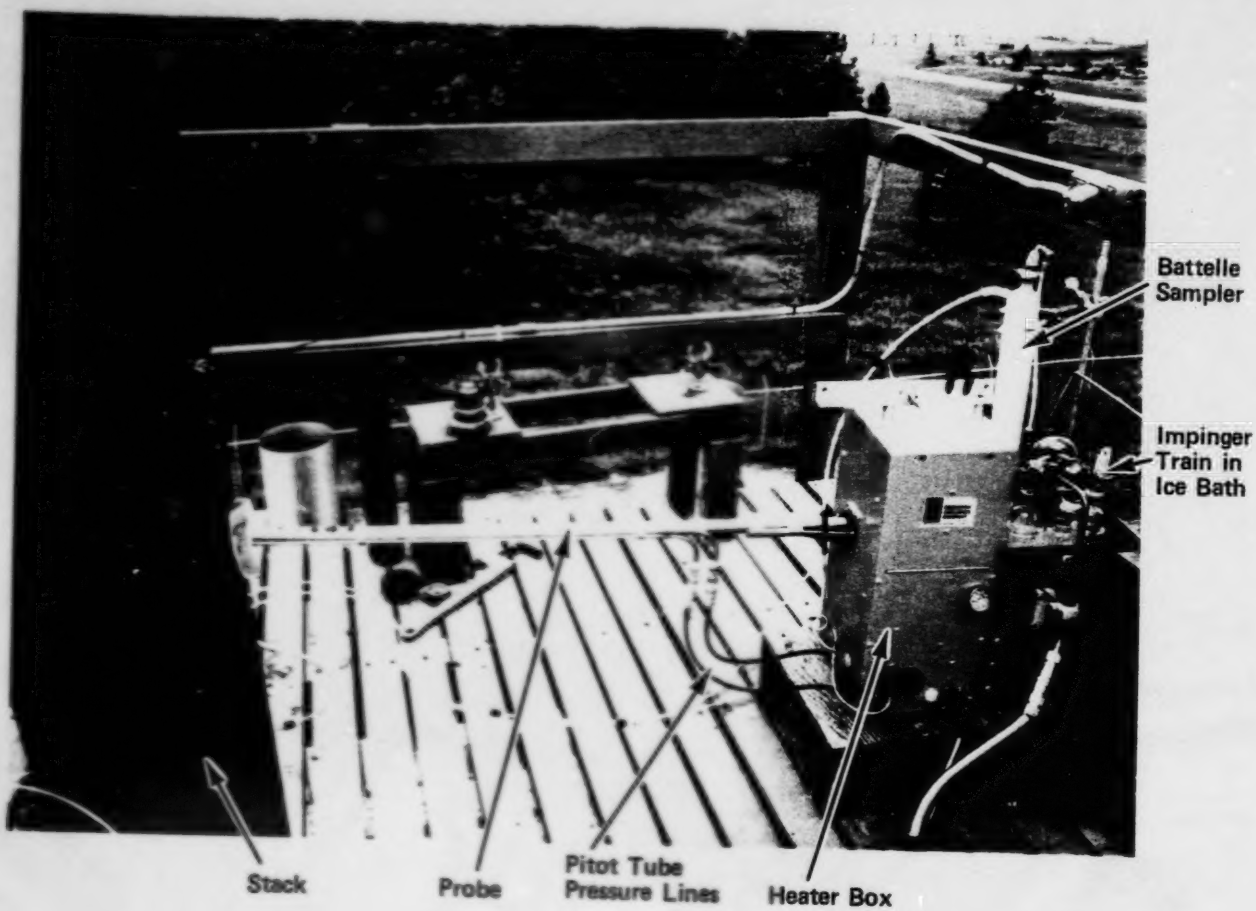
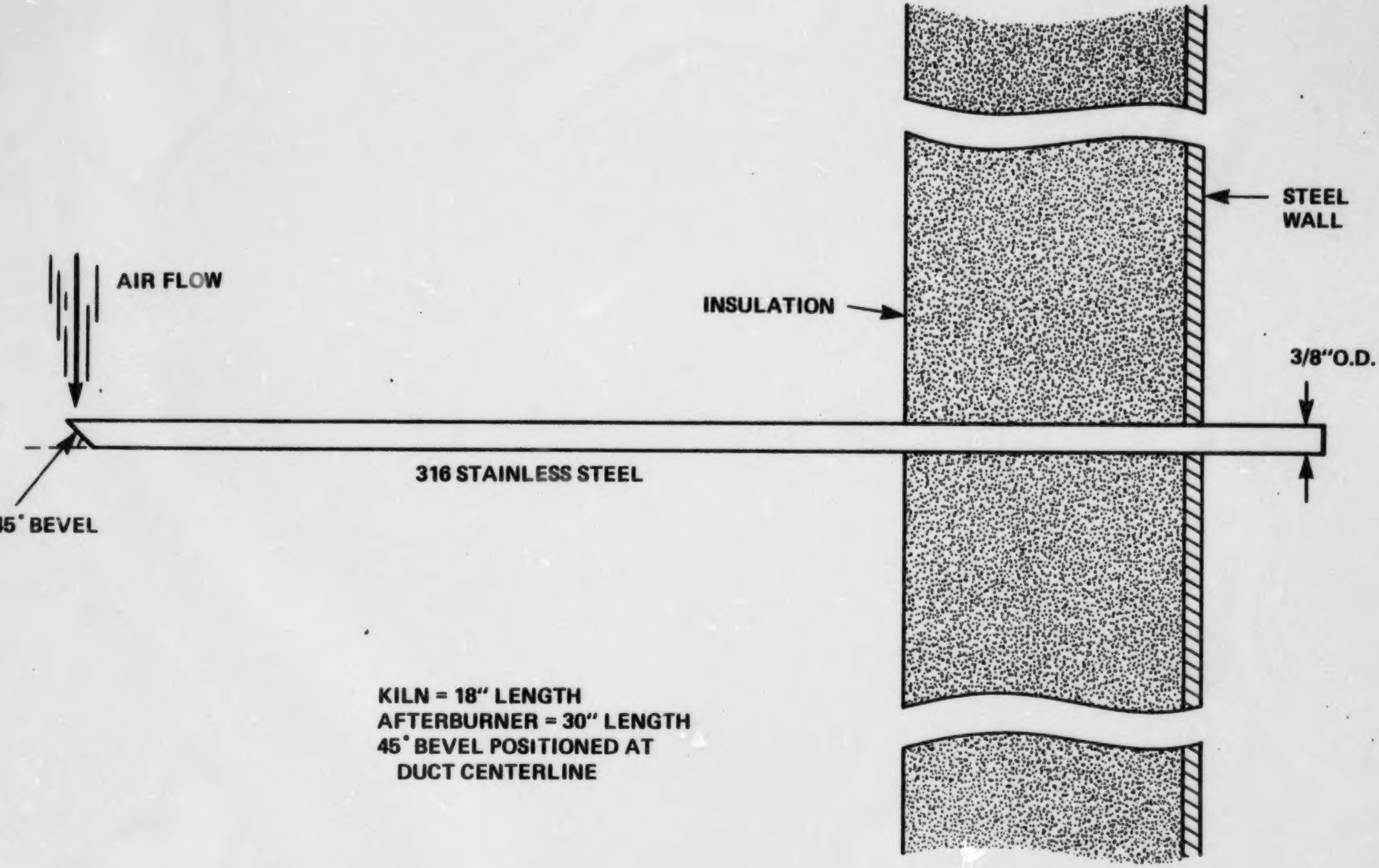

Battelle
Sampler
Impinger
Train in
Ice Bath
Stack
Probe
Pitot Tube
Pressure Lines
Heater Box

FIGURE 15. MODIFIED METHOD 5 SAMPLING TRAIN


AIR FLOW
45° BEVEL
316 STAINLESS STEEL
INSULATION
STEEL WALL
3/8"O.D.

KILN = 18" LENGTH
AFTERBURNER = 30" LENGTH
45° BEVEL POSITIONED AT
DUCT CENTERLINE

FIGURE 16. HOT ZONE SAMPLING PROBE

each use since the precipitated material was part of the sample; this was a very arduous task which was eliminated by use of the shortened stainless lines.

Generally, sampling at any given point did not begin until about 20-30 minutes after the beginning of feed. The exceptions to this will be discussed in their proper place. Further, sampling for organic species was conducted over the range of 10-20 l/min for a time sufficient to collect at least 0.5 DSCM of gas sample. Here again, there were exceptions that will be discussed below.

EXPERIMENTAL DATA

Experiments wherein the system was sampled for residual organic compounds, whether with POHC feed or not, are designated as analytical experiments as differentiated from experiments whose sole purpose was production of engineering-type data. Specific tests are identified by both the date and the time that the sample was taken. For example, an afterburner exit duct sample taken on January 26 at 1235 hours is designated by the identification number A01261235 (A=Afterburner, K=Kiln, S=Stack, M=Misc.; these letters serve as prefixes to the date/time signature) and is so reported in what follows. This somewhat arbitrary division into engineering and/or analytical experiments has been introduced in order to better identify the incinerator conditions that can be expected to have influenced the experimental outcome and also to decrease the redundancy in the data tables that follow.

Experimental Conditions

Table 34 is a listing of the analytical experiments with specific information on the samples taken to determine the presence of organic chemical species. Table 34 also lists the method of sampling that was utilized.

The details of the sampling carried out in the analytical experiments are tabulated in Table 35. Further, a summary of the kiln conditions (for the specific experimental samples identified in Table 35) is presented in Table 36. Similarly, the corresponding data for the afterburner are presented in Table 37.

TABLE 34. LIST OF ANALYTICAL EXPERIMENTS

DATE	FEED	SAMPLES TAKEN	METHOD OF SAMPLING
8/02/83	HCB/Tol*	S08021050	Method 5
		S08021250	Method 5
8/10/83	HCB/Tol	S08101045	Method 5
		S08101300	Method 5
8/12/83	HCB/Tol	S08121000	Method 5
		S08121130	Method 5
8/19/83	HCB/Tol	S08190950	Method 5
		S08191130	Method 5
8/23/83	Propane	S08230945	Method 5
		S08231107	Method 5
8/25/83	Propane	S08251110	Method 5
		S08251250	Method 5
9/01/83	1,2,4-TCB	S09011035	Method 5
		S09011212	Method 5
9/06/83	1,2,4-TCB	S09061046	Method 5
		S09061225	Method 5
9/08/83	1,2,4-TCB	S09081116	Method 5
		S09081258	Method 5
9/13/83	Propane*	S09131057	Method 5
		S09131224	Method 5
9/22/83	Propane	S09221138A	Method 5 (traverse)
		S09221138B	Method 5 (fixed Probe)
10/20/83	Propane	K10201120	Mod. Method 5
		A10201120	Mod. Method 5
10/26/83	Propane	K10261107	Mod. Method 5
		A10261107	Mod. Method 5
		K10261248	Mod. Method 5
		A10261248	Mod. Method 5
10/29/83	Propane/Tol	K10281100	Mod. Method 5
		A10281100	Mod. Method 5
		K10281248	Mod. Method 5
		A10281248	Mod. Method 5

TABLE 34 (Continued)

DATE	FEED	SAMPLES TAKEN	METHOD OF SAMPLING
11/01/83	1,2,4-TCB/Tol	K11011139	Mod. Method 5
		A11011139	Mod. Method 5
		K11011302	Mod. Method 5
		A11011302	Mod. Method 5
11/03/83	Propane/Tol	K11031041	Mod. Method 5
		A11031041	Mod. Method 5
		K11031207	Mod. Method 5
		A11031207	Mod. Method 5
11/09/83	Propane/Tol	K11091008	Mod. Method 5
		A11091008	Mod. Method 5
		K11091136	Mod. Method 5
		A11091136	Mod. Method 5
11/11/83	1,2,4-TCB/Tol	K11111039	Mod. Method 5
		A11111039	Mod. Method 5
		K11111210	Mod. Method 5
		A11111210	Mod. Method 5
11/18/83	1,2,4-TCB/Tol	K11181113	Mod. Method 5
		K11181125	Mod. Method 5
		K11181136	Mod. Method 5
		A11181113	Mod. Method 5
11/22/83	1,2,4-TCB/Tol	K11221045	Mod. Method 5
		A11221045	Mod. Method 5
		K11221205	Mod. Method 5
		A11221205	Mod. Method 5
12/06/83	1,2,4-TCB/Tol	K12061309-1	Mod. Method 5
		K12061309-2	Mod. Method 5
		K12061309-3	Mod. Method 5
12/13/83	Propane	K12131022	Mod. Method 5
		K12131040	Mod. Method 5
		K12131224	Mod. Method 5
1/13/84	1,2,4-TCB	K01131109	Mod. Method 5
		K01131211	Mod. Method 5
		K01131252	Mod. Method 5
		A01131109	Mod. Method 5

TABLE 34 (Continued)

DATE	FEED	SAMPLES TAKEN	METHOD OF SAMPLING
1/24/84	Propane	K01241050	Mod. Method 5
	"	A01241050	Mod. Method 5
	Propane + Tol	K01241225	Mod. Method 5
	"	A01241225	Mod Method 5
	1,2,4-TCB/Tol	K01241350	Mod Method 5
	"	A01241350	Mod Method 5
1/26/84	Propane	K01261120	Mod. Method 5
	"	A01261120	Mod. Method 5
	Propane + Tol	K01261323	Mod. Method 5
	"	A01261322	Mod. Method 5
	HCB/Tol	K01261444	Mod. Method 5
	"	A01261444	Mod. Method 5

*Samples discarded because of low recovery of internal standard (spike).

NOTE: PREFIX S = STACK SAMPLE
A = AFTERBURNER EXIT DUCT
K = KILN EXIT DUCT

TABLE 35. SAMPLING DATA

Date	Site	Sampling Media	Sampling Rate [DSCMM]	Total Sample [DSCM]	Sample ID
8/2/83	S	ISOOCTANE	[Lost Sample]		S08021050
	S	"	0.0107	0.748	S08021250
8/10/83	S	ISOOCTANE	0.0125	0.689	S08101045
	S	"	0.0122	0.698	S08101300
8/12/83	S	ISOOCTANE	0.0089	0.534	S08121000
	S	"	0.0089	0.501	S08121130
8/19/83	S	ISOOCTANE	0.0076	0.456	S08190950
	S	"	0.0066	0.400	S08191130
8/23/83	S	ISOOCTANE	0.0066	0.394	S08230945
	S	"	0.0060	0.351	S08231107
8/25/83	S	ISOOCTANE	0.0105	0.629	S08251110
	S	"	0.0106	0.635	S08251250
9/1/83	S	ISOOCTANE	0.013	0.787	S09011035
	S	"	0.0095	0.567	S09011212
9/6/83	S	ISOOCTANE	0.0097	0.558	S09061046
	S	"	0.0094	0.563	S09061225
9/8/83	S	ISOOCTANE	0.0108	0.645	S09081116
	S	"	0.0081	0.487	S09081258
9/13/83	S	ISOOCTANE	(Lost Sample)		S09131057
	S	"	0.0089	0.570	S09131224
9/22/83	S	ISOOCTANE	0.0093	0.560	S09221138A
	S	"	0.0089	0.533	S09221138B
See Section 6 for more detail on this Experiment					
10/20/83	K	XAD-2	0.0100	1.406	K10201120
	A	"	0.0122	1.710	A10201120
10/26/83	K	XAD-2	0.00845	0.803	K10261107
	A	"	0.0118	1.12	A10261107
	K	"	0.0091	0.748	K10261248
	A	"	0.0093	0.763	A10261248
10/28/83	K	XAD-2	0.011	1.002	K10281100
	A	"	0.0132	0.951	A10281100
	K	"	0.0101	0.918	K10281248
	A	"	0.0136	0.978	A10281248

TABLE 35 (Continued)

Date	Site	Sampling Media	Sampling Rate [DSCMM]	Total Sample [DSCM]	Sample ID
11/01/83	K	"	0.0169	1.011	K11011139
	A	"	0.0158	0.949	A11011139
	K	"	0.00994	0.775	K11011302
	A	"	0.0131	1.021	A11011302
11/03/83	K	XAD-2	0.0160	1.182	K11031041
	A	"	0.0158	1.168	A11031041
	K	"	0.0157	1.335	K11031207
	A	"	0.0122	1.035	A11031207
11/09/83	K	XAD-2	0.0145	1.085	K11091008
	A	"	0.0139	1.045	A11091008
	K	"	0.0136	0.991	K11091136
	A	"	0.0150	1.098	A11091136
11/11/83	K	XAD-2	0.0141	1.087	K11111039
	A	"	0.0134	1.032	A11111039
	K	"	0.0132	1.08	K11111210
	A	"	0.0137	1.127	A11111210
11/18/83	K	XAD-2	0.0216	0.009	K11181113
	K	"	0.0192	0.008	K11181125
	K	"	0.0288	0.012	K11181136
	A	"	0.0147	1.055	A11181113
11/22/83	K	XAD-2	0.0161	1.130	K11221045
	A	"	0.0156	1.090	A11221045
	K	"	0.0154	1.075	K11221205
	A	"	0.01556	1.089	A11221205
12/6/83	K	XAD-2	0.00915	0.824	K12061309A_1
	K	"	0.00903	0.813	K12061309A_2
	K	"	0.00897	0.807	K12061309A_3
12/13/83	K	"	[Lost Sample]		K12131022
	K	"	0.0173	1.225	K12131040
	K	"	0.0170	1.190	K12131224
1/13/84	K	XAD-2	0.0046	0.092	K01131109
	K	"	0.0076	0.0456	K01131211
	K	"	0.0079	0.103	K01131252
	A	"		0.118	A01131109

TABLE 35 (Continued)

Date	Site	Sampling Media	Sampling Rate [DSCMM]	Total Sample [DSCM]	Sample ID
1/24/84	K	XAD-2	0.020	0.793	K01241050
	A	"	0.0103	0.400	A01241050
	K	"	0.016	0.800	K01241225
	A	"	0.0079	0.377	A01241225
	K	"	0.015	0.795	K01241350
	A	"	0.0077	0.420	A01241350
1/26/84	K	XAD-2	0.016	0.880	K01261120
	A	"	0.0095	0.521	A01261120
	K	"	0.0012	0.026	K01261323
	A	"	0.00929	0.195	A01261322
	K	"	0.00489	0.088	K01261444
	A	"	0.0106	0.170	A01261444

TABLE 36. KILN CONDITIONS

Sample ID	Kiln Temp °C (°F)	O_2 (%)	CO_2 (%)	CO (ppm)	Q(Flue Gas) [DSCMM]	Propane Feed [DSCMM]	Heat Release (KJ/H)x10-5	POHC Feed Rate [g/hr]
S08021050	871(1600)	N/A	N/A	N/A	N/A	N/A	N/A	HCB 100
S08021250	871(1600)	N/A	N/A	N/A	N/A	N/A	N/A	HCB 100
S08101045	871(1600)	N/A	N/A	N/A	N/A	N/A	N/A	HCB 100
S08101300	871(1600)	N/A	N/A	N/A	N/A	N/A	N/A	HCB 100
S08121000	760(1400)	10.9	N/A	N/A	10.28	N/A	—	HCB 100
S08121130	760(1400)	10.9	N/A	N/A	10.28	N/A	—	HCB 100
S08190950	700(1280)	6.1	N/A	N/A	5.35	.112	6.133	HCB 100
S08191130	715(1319)	7.6	N/A	N/A	4.89	.115	6.30	HCB 100
S08230945	643(1190)	N/A	N/A	N/A	7.0	.112	6.133	
S08231107	685(1265)	N/A	N/A	N/A	5.35	.115	6.30	
S08251110	871(1600)	N/A	N/A	N/A	7.9	.324	17.74	
S08251250	871(1600)	N/A	N/A	N/A	7.9	.271	14.84	
S09011035	871(1600)	N/A	N/A	N/A	8.4	.206	11.28	TCB 250
S09011212	871(1600)	N/A	N/A	N/A	8.04	.153	8.38	TCB 100
S09061046	871(1600)	N/A	N/A	N/A	7.07	.249	13.63	TCB 500
S09061225	871(1600)	N/A	N/A	N/A	6.80	.222	12.16	TCB 500
S09081116	871(1600)	N/A	N/A	N/A	7.30	.205	11.22	TCB 1000
S09081258	871(1600)	N/A	N/A	N/A	7.30	.209	11.44	TCB 1000
S09131057	871(1600)	N/A	N/A	N/A	not available	.321	17.58	
S09131224	871(1600)	N/A	N/A	N/A	not available	.292	15.99	
S09221138A	871(1600)	N/A	N/A	N/A	9.7	.315	17.25	
S09221138B	871(1600)	N/A	N/A	N/A	9.7	.315	17.25	
K10201120	871(1600)	N/A	N/A	N/A	9.15	N/A	—	
K10261107	871(1600)	N/A	N/A	N/A	7.36	N/A	—	
K10261248	871(1600)	N/A	N/A	N/A	7.36	N/A	—	

TABLE 36 (Continued)

Sample ID	Kiln Temp °C (°F)	O_2 (%)	CO_2 (%)	CO (ppm)	Q(Flue Gas) [DSCMM]	Propane Feed [DSCMM]	Heat Release (KJ/H)x10-5	POHC Feed Rate [g/hr]
K10291100	871(1600)	N/A	N/A	N/A	8.4	N/A	-	
K10291248	871(1600)	N/A	N/A	N/A	8.75	N/A	-	
K11011139	760(1400)	N/A	N/A	N/A	10.4	.324	17.74	
K11011302	760(1400)	N/A	N/A	N/A	8.9	.285	15.61	
K11031041	760(1400)	8.75	N/A	N/A	8.5	N/A	-	
K11031207	760(1400)	8.75	N/A	N/A	7.0	N/A	-	
K11091008	760(1400)	N/A	N/A	N/A	7.5	N/A	-	
K11091136	760(1400)	N/A	N/A	N/A	6.6	N/A	-	
K11111039	871(1600)	N/A	N/A	N/A	7.5	0.275	15.06	TCB 100
K11111210	871(1600)	N/A	N/A	N/A	6.6	0.275	15.06	TCB 100
K11181113	787-760 (1450-1400)	(a)	5.8	<1	5.70	N/A	-	TCB 4000
K11181125	732-704 (1350-1300)	(a)	5.2	2.3	6.28	N/A	-	TCB 4000
K11181136	677-649 (1250-1200)	(a)	5.6	6	8.80	N/A	-	TCB 4000
K11221045	760(1400)	8.25	8.2	<1	9.6	N/A	-	TCB 100
K11221205	760(1400)	9.5	7.5	<1	9.6	N/A	-	TCB 100
K12061309A_1	760(1400)	N/A	N/A	N/A	9.26	N/A	N/A	TCB 100
K12061309A_2	760(1400)							TCB 100
K12061309A_3	760(1400)							TCB 100
K12131022	760(1400)	7.75	8.4	<1	7.70	.212	11.61	
K12131040	760(1400)	7.75	8.4	<1	7.70	.212	11.61	
K12131224	760(1400)	8.25	8.0	<1	7.70	.212	11.61	
K01131109	538(1000)	12.0	0.6	~20	8.57	.154	8.43	TCB 100
K01131211	538(1000)	12.0	0.4	~10	8.57	.154	8.43	TCB 100
K01131252	538(1000)	12.0	0.3	2-4	8.57	.154	8.43	TCB 100
K01241050	538(1000)	N/A	6.4	3	7.6			
K01241225	538(1000)	N/A	7.7	2	7.6			
K01241350	538(1000)	N/A	7.8	>100	7.6			TCB 100
K01261120	510(950)	10.7	6.3	>100	8.49	.141	7.72	
K01261323	510(950)	11.5	6.3	>100	8.49	.141	7.42	
K01261444	510(950)	11.7	6.1	>100	8.49	.141	7.72	HCB 100

(a) O_2 meter problems
N/A = Not available

TABLE 37. AFTERBURNER CONDITIONS

SAMPLE ID	AB TEMP °C (°F)	COMBUSTION GASES O_2 (%)	CO_2 (%)	CO (PPM)	FLOW(Q) [DSCMM]	PROPANE [DSCMM]	t_r (V/Q) (SEC)	STACK EXCESS AIR (%)
S08021050	1093(2000)	12	6.5	<1	17.93	.329	1.23	109.09
S08021250	1093(2000)	12	6.2	<1	17.93	.329	1.23	109.09
S08101045	1093(2000)	7.5	8.0	<1	17.45	N/A	1.28	66.00
S08101300	1093(2000)	7.5	8.1	<1	17.45	N/A	1.28	64.29
S08121000	982(1800)	10.0	7.4	<1	15.71	N/A	1.53	76.92
S08121130	982(1800)	10.0	7.4	<1	15.71	N/A	1.53	76.92
S08190950	877(1610)	11.0	7	<1	13.79	.222	1.91	92.00
S08191130	877(1610)	11.0	7	<1	13.79	.206	1.91	100.00
S08230945	877(1610)	10.0	7.2	<1	13.50	.257	1.95	76.92
S08231107	877(1610)	10.0	6.5	<1	14.70	.247	1.79	100.00
S08251110	1093(2000)	7.0	8.4	<1	17.5	.347	1.26	43.75
S08251250	1093(2000)	7.0	8.4	<1	17.3	.332	1.28	48.39
S09011035	1071(1960)	7.5	8.6	<1	16.7	.329	1.35	43.75
S09011212	1071(1960)	16.3	4.5	<1	14.5	.329	1.55	187.50
S09061046	1066(1950)	7.0	8.6	<1	16.05	.329	1.41	45.00
S09061225	1093(2000)	7.0	8.2	<1	16.90	.321	1.31	50.00
S09081116	1093(2000)	7.5	8.4	<1	16.9	.343	1.31	50.00
S09081258	1093(2000)	7.5	8.0	<1	16.0	.315	1.42	56.00
S09131057	1093(2000)	8.2	(a)	~	18.6	.328	1.19	48.38
S09131224	1093(2000)	(a)	(a)	~	18.6	.319	1.19	53.33
S09221138A	1093(2000)	8.5	7.3	<1	21.0	.341	1.05	58.62
S09221138B	1093(2000)	8.5	7.3	<1	21.0	.341	1.05	58.62
A10201120	1093(2000)	8	7.6	~0	16.0	N/A	1.38	58.62
A10261107	1093(2000)	(a)	(a)	(a)	17.2	N/A	1.28	58.62
A10261248	1093(2000)	(a)	(a)	(a)	17.2	N/A	1.28	61.40

TABLE 37 (Continued)

SAMPLE ID	AB TEMP °C (°F)	COMBUSTION GASES O_2 (%)	CO_2 (%)	CO (PPM)	FLOW(Q) [DSCMM]	PROPANE [DSCMM]	t_r (V/Q) (SEC)	STACK EXCESS AIR (%)
A10281100	1093(2000)	7.5	8.4	<1	16.5	N/A	1.34	48.39
A10281248	1093(2000)	8.25	8.0	<1	15.4	N/A	1.33	55.93
A11011139	982(1800)	(a)	(a)	(a)	16.35	.218	1.47	N/A
A11011302	982(1800)	(a)	(a)	(a)	15.40	.210	1.57	N/A
A11031041	871(1600)	11.25	6.4	<1	15.0	N/A	1.76	91.67
A11031207	871(1600)	10.50	7.1	~1	1204	N/A	2.13	84.00
A11091008	871(1600)	10.5	6.6	<1	14.6	N/A	1.81	76.92-162.8
A11091136	871(1600)	11.0	6.2	<1	13.7	N/A	1.93	84.00-162.8
A11111039	1093(2000)	6.5	8.8	<1	15.2	0.309	1.45	N/A
A11111210	1093(2000)	6.5	8.0	<1	15.2	0.309	1.45	N/A
A11181113	1093(2000)	7.5	8.0	<1	17.43	N/A	1.27	46.03-104.4
A11221045	871(1600)	8.50	8.0	~2	16.0	N/A	1.65	95.74
A11221205	871(1600)	8.0	7.1	~2	16.0	N/A	1.65	95.74
A1206-(b)	871(1600)	N/A	N/A	N/A	15.6	N/A	1.87	73.6
A1213-(b)	977(1790)	6.0	9.2	<1	12.4	0.16	2.36	61.4
A01131109	1027(1880)	8.5	9.5	~1.5	14.45	.155	2.16	119.05
A01241050	899(1650)	10	7.6	<1	13.6	"	2.32	74
A01241225	899(1650)	10.5	7.5	<1	13.6	"	2.25	84
A01241350	899(1650)	10.7	7.4	<1	13.6	"	2.30	84
A01261120	815(1500)	11.5	5.2	<1	13.67	.155	2.40	100.00
A01261323	815(1500)	10.75	5.5	<1	13.67	.155	2.35	84.00
A01261444	815(1500)	11.00	6.1	<1	13.67	.155	2.31	100.00

(a) Meter problems
(b) No sample taken

Analytical Data

In order to simplify the reporting of the analytical data for the numerous experiments discussed above, specific analytes are identified by the abbreviations tabulated in Table 38. In addition, the concentration of each compound in the most dilute standard solution used to calibrate the gas chromatograph is noted.

If an incinerator sample of approximately 1.0 DSCM is represented by an extract whose volume is 10.0 ml, and the average gas flows at each sampled point of the incinerator are K=kiln = 8.4 DSCMM, A=afterburner = 15.0 DSCMM, and S=stack = 17.4 DSCMM; then the minimum reporting values for each compound at each sampled point are as listed in the right-most three columns of Table 38.

The analytical results obtained for all of the HCB and TCB test series are tabulated in Table 39.

DESTRUCTION EFFICIENCY (DE) AND DESTRUCTION AND REMOVAL EFFICIENCIES (DRE) FOR POHCs

System DRE Results

In the course of the experiments reported herein, the DRE of the entire system has been measured for the two POHCs, HCB and 1,2,4-TCB, at a variety of incinerator operating conditions. Table 40 presents a summary of the input-output data and DRE values from these experiments, plus afterburner temperature and residence time for each experiment, derived from the analytical results in Table 39. As can be seen, in all cases the DRE was well above the 99.99% limits prescribed by the RCRA regulation.

From the data on Table 40, there appears to have been essentially no variation of measured DRE for either HCB or TCB with combined temperature/residence times. Over the feed rate range covered of 100 to 1000 gm/hr, there also was no discernable effect of feed rate on DRE. Except for excursions during startup and shutdown, carbon monoxide levels were below 1 ppm during all of these tests; thus, the CO level did not appear dependent on feed rate or temperature/residence time over the range covered.

TABLE 38. IDENTITY OF STANDARD COMPOUNDS USED

ABBREVIATION	CHEMICAL NAME	STD. CONC. (μg/ml)	MINIMUM REPORTING VALUES* (μg/min) K	A	S
CL5-EANE	PENTACHLOROETHANE	0.000656	0.055	0.098	0.11
1,3-DCBZ(m)	1,3-DICHLOROBENZENE	0.00921	0.77	1.4	1.6
1,4-DCBZ(p)	1,4-DICHLOROBENZENE	0.0202	1.7	3.0	3.5
CL6-EANE	HEXACHLOROETHANE	0.00512	0.43	0.77	0.89
1,2-DCBZ(O)	1,2-DICHLOROBENZENE	0.00780	0.66	1.2	1.4
BENZYL CL	BENZYL CHLORIDE	0.00800	0.67	1.2	1.4
1,3,5-TCBZ	1,3,5-TRICHLOROBENZENE	0.00344	0.29	0.52	0.60
HC-1,3-BD	HEXACHLORO-1,3-BUTADIENE	0.000800	0.067	0.12	0.14
1,2,4-TCBZ	1,2,4-TRICHLOROBENZENE	0.00499	0.42	0.75	0.87
1,2,4,5-TCBZ	1,2,4,5-TETRACHLOROBENZENE	0.000853	0.072	0.13	0.15
1,2,3,4-TCBZ	1,2,3,4-TETRACHLOROBENZENE	0.000490	0.041	0.072	0.085
2-CL-NAPHTH	2-CHLORONAPHTHALENE	0.0222	1.9	3.3	3.9
CL5-BZ	PENTACHLOROBENZENE	0.000437	0.037	0.066	0.077
CL6-BZ	HEXACHLOROBENZENE	0.00102	0.086	0.15	0.18
ALPHA-BHC	1,2,3,4,5,6-HEXACHLOROCYCLOHEXANE, α-ISOMER	0.00200	0.17	0.30	0.35
GAMMA-BHC	1,2,3,4,5,6-HEXACHLOROCYCLOHEXANE, γ-ISOMER	0.00366	0.31	0.55	0.64
1,2,3,4-TCNAPHTH	1,2,3,4-TETRACHLORONAPHTHALENE	0.00400	0.34	0.61	0.70
DEP	DIETHYL PHTHALATE	0.00257	0.22	0.39	0.46
DNBP	DI-n-BUTYL PHTHALATE	0.0104	0.87	1.6	1.8
BUBZP	BUTYLBENZYL PHTHALATE	0.00486	0.41	0.73	0.85
F8-BIPHENYL	OCTAFLUOROBIPHENYL	0.0200	1.7	3.0	3.5

*K = kiln; A = afterburner; S = stack

TABLE 39. SUMMARY OF RESULTS OF POHC AND PIC ANALYSES OF INCINERATOR SAMPLES

SAMPLE I.D. NUMBER	S0810-1045	S0810-1300	S0812-1000	S0812-1130	S0819-0950	S0819-1130	S0823-0945	S0823-1107	S0825-1250	S0901-1035	S0901-1212	S0906-1046	S0906-1225	S0908-1116	S0908-1258	S0913-1224	S0922-1138	K1020-1120
Analyte (µg/min)																		
CL5-EANE	<0.11	<0.11	<0.11	0.231	<0.11	<0.11	0.266	<0.11	<0.11	<0.11	<0.11	<0.11	0.280	<0.11	<0.11	<0.11	5.13	<0.055
1,3-DCBZ(m)	41.6	43.8	45.3	63.3	48.9	51.1	47.8	78.8	52.9	46.3	60.2	78.9	45.8	97.9	107	50.1	104	<0.77
1,4-DCBZ(p)	<3.5	13.5	<3.5	<3.5	<3.5	5.98	11.5	17.4	8.01	<3.5	<3.5	17.5	<3.5	25.1	29.6	<3.5	<3.5	<1.7
CL6-EANE	10.6	18.3	15.2	10.6	8.63	2.70	1.09	22.8	16.8	13.3	10.9	<0.89	<0.89	<0.89	<0.89	11.2	31.7	<0.43
1,2-DCBZ(0)	7.50	<1.4	<1.4	<1.4	8.11	<1.4	28.5	41.1	<1.4	<1.4	<1.4	<1.4	<1.4	<1.4	<1.4	<1.4	<1.4	<0.66
BENZYL CL	32.8	31.3	37.7	56.7	39.0	44.5	43.5	52.1	33.9	38.7	49.0	54.4	45.4	35.6	57.7	38.7	69.6	<0.67
1,3,5-TCBZ	<0.60	3.13	<0.60	<0.60	<0.60	<0.60	<0.60	2.29	<0.60	<0.60	<0.60	<0.60	<0.60	<0.60	<0.60	<0.60	<0.60	<0.29
HC-1,3-BD	<0.14	0.871	<0.14	<0.14	0.60	<0.14	1.12	0.940	<0.14	<0.14	<0.14	0.338	0.348	<0.14	<0.14	0.358	0.947	<0.067
1,2,4-TCBZ	2.82	7.15	1.50	3.64	2.77	3.79	<0.87	10.8	4.72	4.22	5.12	11.2	14.4	31.7	45.6	28.0	21.3	0.607
1,2,4,5-TCBZ	3.15	3.16	4.49	6.11	3.94	2.52	11.7	5.97	8.38	2.77	5.32	13.1	10.5	6.84	14.5	5.29	6.00	<0.072
1,2,3,4-TCBZ	3.27	<0.085	<0.085	1.97	<0.085	<0.085	<0.085	<0.085	<0.085	<0.085	<0.085	1.71	<0.085	<0.085	<0.085	<0.085	<0.085	<0.041
2-CL-NAPHTH	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<3.9	<1.9
CL5-BZ*	87%	82%	83%	84%	76%	85%	71%	96%	89%	93%	81%	82%	94%	64%	100%	73%	88%	1.61
CL6-BZ	8.36	27.6	73.6	57.8	37.2	34.7	40.4	35.5	14.9	7.42	17.6	23.7	22.8	13.1	21.5	21.0	22.7	2.30
ALPHA-BHC	1.70	8.06	<0.35	5.00	<0.35	2.76	11.8	<0.35	<0.35	<0.35	1.12	<0.35	1.78	<0.35	<0.35	<0.35	<0.35	1.50
GAMMA-BHC	<0.64	11.5	1.68	3.64	2.33	2.68	<0.64	2.02	<0.64	<0.64	0.886	<0.64	<0.64	<0.64	<0.64	1.97	1.30	<0.31
1,2,3,4-TCNAPHTH	<0.70	28.7	<0.70	<0.70	2.71	<0.70	<0.70	<0.70	<0.70	<0.70	<0.70	<0.70	<0.70	1.86	<0.70	<0.70	<0.70	2.58
DEP																		12,900
DNBP																		227
BUBZP																		16.9

*A percent figure in this row indicates recovery of CL5-BZ spike (1.38 µg in impinger #2) added to the Method 5 train prior to sampling.

TABLE 39. SUMMARY OF RESULTS OF POHC AND PIC ANALYSES OF INCINERATOR SAMPLES (Con't)

SAMPLE I.D. NUMBER	A1020-1120	K1026-1107	A1026-1107	K1026-1248	A1026-1248	K1028-1100	A1028-1100	K1028-1248	A1028-1248	K1101-1139	A1101-1139	K1101-1302	A1101-1302	K1103-1041	A1103-1041	K1103-1207	A1103-1207	K1109 1008
Analyte (µg/min)																		
CL5-EANE	<0.098	0.256	0.296	0.289	0.436	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	<0.055
1,3-DCBZ(m)	<1.4	46.8	<1.4	50.2	1.94	<0.77	<1.4	<0.77	<1.4	<0.77	<1.4	<0.77	<1.4	<0.77	<1.4	<0.77	<1.4	<0.77
1,4-DCBZ(p)	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7
CL6-EANE	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	0.482
1,2-DCBZ(O)	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66
BENZYL CL	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67	<1.2	<0.67
1,3,5-TCBZ	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29	<0.52	<0.29
HC-1,3-BD	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067
1,2,4-TCBZ	0.772	1.41	1.10	1.34	1.43	<0.42	<0.75	<0.42	<0.75	<0.42	<0.75	<0.42	<0.75	<0.42	<0.75	<0.42	<0.75	<0.42
1,2,4,5-TCBZ	<0.13	<0.072	0.306	<0.072	0.449	<0.072	<0.13	<0.072	<0.13	<0.072	<0.13	<0.072	<0.13	<0.072	<0.13	<0.072	<0.13	<0.072
1,2,3,4-TCBZ	<0.072	0.651	<0.072	0.699	<0.072	<0.041	<0.072	<0.041	<0.072	<0.041	<0.072	<0.041	<0.072	<0.041	<0.072	<0.041	<0.072	<0.041
2-CL-NAPHTH	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9
CL5-BZ*	0.268	12.5	1.87	13.3	2.68	0.0857	0.0826	0.238	0.0881	0.415	0.108	0.166	<0.066	0.146	0.0671	0.071	<0.066	0.107
CL6-BZ	0.675	<0.086	6.48	<0.086	9.75	<0.086	0.19	0.126	0.200	0.135	<0.15	<0.086	<0.15	<0.086	<0.15	<0.086	<0.15	<0.086
ALPHA-BHC	0.550	<0.17	<0.30	<0.17	2.91	<0.17	<0.30	<0.17	<0.30	<0.17	<0.30	<0.17	<0.30	<0.17	<0.30	<0.17	<0.30	0.392
GAMMA-BHC	<0.55	0.326	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	0.681
1,2,3,4-TCNAPHTH	7.93	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34
DEP	2960	1810	738	1590	813	67.2	206	189	227	134	120	123	82.9	90.1	54.3	54.7	69.5	66.5
DNBP	1850	388	1040	268	1100	91.2	328	172	284	148	218	206	242	231	291	161	315	477
BUBZP	24.5	29.3	45.2	31.5	66.3	27.8	<0.73	<0.41	52.3	<0.41	<0.73	<0.41	<0.73	<0.41	<0.73	1.38	<0.73	10.1
FB-BIPHENYL**														103%	100%	104%	103%	113%

* A percent figure in this row indicates recovery of CL5-BZ spike (1.38 µg in impinger #2) added to the Method 5 train prior to sampling.

**A percent figure in this row indicates recovery of FB-Biphenyl spike (20.0 mg) added to the XAD-2 adsorbant in each Battelle sampler prior to sampling. No entry in this row indicates that the FB-Biphenyl spike was not used, or that chromatographic interference made it impossible to determine its recovery train prior to sampling.

TABLE 39. SUMMARY OF RESULTS OF POHC AND PIC ANALYSES OF INCINERATOR SAMPLES (Con't)

SAMPLE I.D. NUMBER	A1109-1008	K1109-1136	A1109-1136	K1111-1039	A1111-1039	K1111-1210	A1111-1210	K1118-1113	K1118-1125	K1118-1136	A1118-1113	K1122-1045	A1122-1045	K1122-1205	A1122-1205	K1206-1309-1	K1206-1309-2	K1206-1309-3
Analyte (µg/min)																		
CL5-EANE	0.371	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	<0.055	<0.055	<0.055	<0.098	0.337	<0.098	<0.055	<0.098	13.4	<0.055	0.139
1,3-DCBZ(m)	<1.4	<0.77	<1.4	0.735	<1.4	0.142	<1.4	<0.77	<0.77	<0.77	<1.4	10.3	<1.4	4.55	<1.4	<0.77	<0.77	<0.77
1,4-DCBZ(p)	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<1.7	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	3.49	4.42	4.52
CL6-EANE	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.43	≤0.43	<0.77	<0.43	<0.77	<0.43	<0.77	13.1	<0.43	<0.43
1,2-DCBZ(O)	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<0.66	536	<1.2	<0.66	<1.2	<0.66	12.1	<0.66	<0.66	<0.66
BENZYL CL	<1.2	<0.67	<1.2	38.8	21.3	39.1	19.5	<0.67	<0.67	<0.67	<1.2	983	4,680	1,030	4,680	1.29	1.31	1.33
1,3,5-TCBZ	<0.52	<0.29	<0.52	0.361	<0.52	<0.29	<0.52	<0.29	<0.29	15,000	<0.52	<0.29	<0.52	1.02	<0.52	<0.29	<0.29	<0.29
HC-1,3-BD	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.067	476	<0.12	0.0932	<0.12	<0.067	<0.12	3.00	<0.067	<0.067
1,2,4-TCBZ	<0.75	<0.42	<0.75	0.976	<0.75	<0.42	<0.75	210	682	884,000	7.59	147	1.20	34.7	4.30	3.73	3.30	3.41
1,2,4,5-TCBZ	<0.13	<0.072	<0.13	1.98	12.2	1.99	11.2	<0.072	<0.072	<0.072	0.193	<0.072	<0.13	<0.072	<0.13	<0.072	<0.072	0.211
1,2,3,4-TCBZ	<0.072	<0.041	<0.072	0.912	<0.072	0.0644	<0.072	<0.041	<0.041	7,810	<0.072	11.7	<0.072	4.32	0.234	0.366	<0.041	<0.041
2-CL-NAPHTH	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	15.7	26.2	<1.9	<3.3	3.96	1.16	4.16	1.16	<1.9	<1.9	<1.9
CL5-BZ*	0.0909	0.0427	0.0815	3.28	<0.066	0.404	<0.066	0.505	5.06	57,200	0.569	80.4	0.103	20.6	3.23	2.42	0.171	0.356
CL6-BZ	<0.15	<0.086	<0.15	0.796	<0.15	0.223	<0.15	<0.086	<0.086	51,300	0.947	74.5	0.485	15.9	3.90	13.8	4.42	6.01
ALPHA-BHC	0.361	<0.17	<0.30	0.793	0.308	0.489	<0.30	<0.17	0.732	57.6	0.564	0.412	<0.30	0.298	<0.30	<0.17	<0.17	<0.17
GAMMA-BHC	<0.55	0.705	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.31	4.44	0.309	<0.31	<0.55	<0.31	<0.55	<0.31	<0.31	<0.31
1,2,3,4-TCNAPHTH	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.34	2,980	<0.61	2.82	<0.61	0.520	<0.61	<0.34	<0.34	<0.34
DEP	89.2	36.9	87.9	105	67.8	52.8	41.7	<0.22	<0.22	2,390	267	<0.22	16.5	3.20	<0.39	17.8	2.69	2.72
DNBP	501	465	492	36.9	72.2	26.0	44.5	<0.87	<0.87	37,100	3,400	89.8	95.9	86.9	95.2	41.5	33.0	43.3
BUBZP	16.7	9.93	16.3	5.88	4.10	5.92	3.76	51.3	231	5,580	24.1	18.5	20.0	18.8	22.9	19.3	7.50	6.73
FB-BIPHENYL**	89%	103%	119%	96%	84%	102%	116%	112%	105%		122%		99%	105%	103%	89%	107%	102%

* A percent figure in this row indicates recovery of CL5-BZ spike (1.38 µg in impinger #2) added to the Method 5 train prior to sampling.

**A percent figure in this row indicates recovery of FB-Biphenyl spike (20.0 mg) added to the XAD-2 adsorbant in each Battelle sampler prior to sampling. No entry in this row indicates that the FB-Biphenyl spike was not used, or that chromatographic interference made it impossible to determine its recovery train prior to sampling.

TABLE 39 (Continued)

SAMPLE I.D. NUMBER	K1213-1022	K1213-1040	K1213-1224	K0113-1109	K0113-1211	K0113 1252	A0113 1109	K0124 1050	A0124 1050	K0124-1225	A0124-1225	K0124-1350	A0124-1350	K0126-1120	A0126-1120	K0126-1323	A0126-1323	K0126-1444
Analyte (μg/min)																		
CL5-EANE	<0.055	<0.055	<0.055	0.461	<0.055	<0.055	22.6	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098	6.42	0.489	<0.055
1,3-DCBZ(m)	<0.77	<0.77	<0.77	123	129	67.5	<1.4	<0.77	<1.4	<0.77	<1.4	2.67	<1.4	<0.77	<1.4	10.3	<1.4	<1.4
1,4-DCBZ(p)	<1.7	2.34	2.71	18.0	108	20.0	<3.0	<1.7	5.71	<1.7	5.01	4.45	12.2	<1.7	<3.0	<1.7	<3.0	<1.7
CL6-EANE	<0.43	<0.43	<0.43	<0.43	5.88	<0.43	71.8	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77	0.482	<0.77	<0.43	<0.77	<0.43
1,2-DCBZ(0)	<0.66	<0.66	<0.66	67.7	64.4	36.9	<1.2	0.677	<1.2	<0.66	<1.2	14.5	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66
BENZYL CL	<0.67	2.51	1.03	126	36.9	3.92	<1.2	4.62	<1.2	<0.67	21.1	19.7	9.03	6.28	<1.2	983	4,680	1,030
1,3,5-TCBZ	<0.29	<0.29	<0.29	23.9	22.0	10.0	<0.52	<0.29	<0.52	<0.29	<0.52	6.48	<0.52	<0.29	<0.52	2.58	<0.52	1.02
HC-1,3-BD	<0.067	<0.067	<0.067	<0.067	<0.067	<0.067	8.64	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	0.0932	<0.12	<0.067
1,2,4-TCBZ	10.9	<0.42	0.65	10,600	10,100	3,910	3.53	130	1.22	102	<0.75	3,200	2.59	26.2	7.59	147	1.20	34.7
1,2,4,5-TCBZ	<0.072	<0.072	0.192	<0.072	<0.072	<0.072	<0.13	<0.072	<0.13	<0.072	<0.13	<0.072	<0.13	<0.072	0.193	<0.072	<0.13	<0.072
1,2,3,4-TCBZ	<0.041	<0.041	0.300	<0.041	<0.041	0.453	1.29	0.0426	0.411	<0.041	<0.072	<0.041	<0.072	<0.041	<0.072	11.7	<0.072	4.32
2-CL-NAPHTH	<1.9	<1.9	<1.9	<1.9	<1.9	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	3.96	1.16	4.16
CL5-BZ*	0.037	0.0832	0.602	0.839	0.037	0.393	6.44	<0.037	1.29	0.230	<0.066	0.493	0.133	<0.037	0.569	80.4	0.103	20.6
CL6-BZ	<0.086	<0.086	0.147	4.28	9.51	1.11	16.2	0.192	1.29	0.186	<0.15	0.247	0.363	0.156	0.947	74.5	0.485	15.9
ALPHA-BHC	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.30	<0.17	<0.30	<0.17	<0.30	<0.17	<0.30	<0.17	0.564	0.412	<0.30	0.298
GAMMA-BHC	<0.31	<0.31	<0.31	0.866	<0.31	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	<0.55	<0.31	0.309	<0.31	<0.55	<0.31
1,2,3,4-TCNAPHTH	<0.34	<0.34	<0.34	<0.34	<0.34	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	2.82	<0.61	0.528
DEP	72.7	7.31	3.79	136	909	110	7.46	22.4	29.9	16.3	41.8	14.1	17.5	1.68	267	<0.22	16.5	3.20
DNBP	462	3.63	18.6	535	6,450	250	59.8	76.6	99.3	33.0	67.5	76.6	102	4.66	3,400	89.8	95.9	86.9
BUBZP	<0.41	16.1	4.58	147	573	172	14.9	29.2	31.2	2.60	15.8	16.4	3.69	3.00	24.1	18.5	20.0	18.8
FB-BIPHENYL**	102%	107%	105%	89%	78%	108%	85%		72%	93%	85%		75%		122%		99%	105%

* A percent figure in this row indicates recovery of CL5-BZ spike (1.38 μg in impinger #2) added to the Method 5 train prior to sampling.

**A percent figure in this row indicates recovery of FB-Biphenyl spike (20.0 mg) added to the XAD-2 adsorbant in each Battelle sampler prior to sampling. No entry in this row indicates that the FB-Biphenyl spike was not used, or that chromatographic interference made it impossible to determine its recovery train prior to sampling.

TABLE 40. MEASURED DRE VALUES FOR HCB AND 1,2,4-TCB IN TOLUENE

SAMPLE ID	POHC ID	FEED RATE (mg/min)	EMISSION RATE (μg/min)	DRE (%)	TAB (°C)	T_R (sec)
S08101045	HCB	1.67	8.36	99.9995	1093	1.28
S08101300	HCB	1.67	27.6	99.998	1093	1.28
S08121000	HCB	1.67	73.6	99.996	982	1.53
S08121130	HCB	1.67	57.8	99.997	982	1.53
S08190950	HCB	1.67	37.2	99.998	877	1.91
S08191130	HCB	1.67	34.7	99.998	877	1.91
A01261444	HCB	1.67	3.70	99.9998	815	2.31
S09011035	TCB	4.17	5.12	99.9998	1071	1.35
S09011212	TCB	1.67	11.2	99.9993	1071	1.55
S09061046	TCB	8.33	14.4	99.9998	1066	1.41
S09061225	TCB	8.33	31.7	99.9996	1093	1.31
S09081116	TCB	16.66	45.6	99.9997	1093	1.31
S09081258	TCB	16.66	28.0	99.9998	1093	1.42
A11111039	TCB	1.67	<0.75	99.99996	1093	1.45
A11111210	TCB	1.67	<0.75	99.99996	1093	1.45
A11221045	TCB	1.67	1.20	99.99993	871	1.65
A11221205	TCB	1.67	4.30	99.9997	871	1.65
A01241350	TCB	1.67	2.59	99.9998	899	1.65

The DREs for the 1,2,4-TCB appear, from Table 40, generally to be slightly higher than those for HCB, although the errors inherent in the measurements may have been of the same order as the apparent differences in DRE. Nevertheless, since it is generally accepted that the thermal stability of chlorinated benzenes increases as the number of chlorines is increased, the slight but consistent lower DREs for HCB as compared to those for the TCB may actually reflect differences in thermal stability of the two compounds.

Afterburner Destruction Efficiency

Selected data shown in Table 41 represents the measured destruction efficiency in the afterburner (DE_{AB}) for three compounds, HCB, pentachlorobenzene, and 1,2,4-TCB. The feed rate to the afterburner is based on the amount of the compound found in the kiln transfer duct, and the emission rate is based on the amount found in the afterburner transfer duct. In all but the last example on Table 41, sample no. K/A01261444, no chlorinated compounds were in the kiln feed; i.e., the kiln feed was either propane alone or a combination of propane and toluene. The data on Table 41 point up several interesting facts:

- There are points or areas of both the kiln and the afterburner which become contamination with residual levels of the several compounds present either as POHC or as PICs and thereafter serve as sources for these compounds.
- When the feed rate of a compound to the afterburner is high the resulting DE is high; on the other hand, when the feed rate is low, there can be more of the compound emitted than was in the feed. These feed rates, of course, are much smaller than those to the kiln on Table 40.

To date, the specific area in the system where refractory compounds are deposited during feed experiment has not been identified. On the other hand, in every case in which a "no feed" experiment has followed one wherein a chlorinated benzene was fed has exhibited this residue or "hold up" problem. It is also not clear how important this phenomenon might be in commercial scale incineration.

TABLE 41. MEASURED DE_{AB} VALUES FOR HCB, PENTACHLOROBENZENE AND 1,2,4-TCB

SAMPLE ID	POHC ID	FEED RATE (µg/min)	EMISSION RATE (µg/min)	DE_{AB} (%)	TAB (°C)	t_r (sec)
K/A10201120	TCB	0.607	0.772	-27.18	1093	1.38
	CL5-BZ	1.61	0.268	83.35	1093	1.38
	HCB	2.30	0.675	70.65	1093	1.38
K/A10261107	TCB	1.41	1.10	21.99	1093	1.28
	CL5-BZ	12.5	1.87	85.04	1093	1.28
	HCB	<0.086	6.48	-7435	1093	1.28
K/A10261248	TCB	1.34	1.43	-6.72	1093	1.28
	CL5-BZ	13.3	2.68	79.85	1093	1.28
	HCB	<0.086	9.75	-11237	1093	1.28
K/A10281100	CL5-BZ	0.0857	0.0826	3.62	1093	1.34
	HCB	<0.086	0.191	-122	1093	1.34
K/A01261120	TCB	26.2	4.68	82.14	815	2.40
	CL5-BZ	<0.037	0.082	-122	815	2.40
	HCB	0.156	0.190	-21.8	815	2.40
K/A01261323	TCB	61.8	4.16	93.3	815	2.35
	CL5-BZ	1.35	0.271	79.3	815	2.35
	HCB	2.49	0.518	79.2	815	2.35
K/A01261444	TCB	632	4.21	99.33	815	2.31
	CL5-BZ	63.7	0.393	99.38	815	2.31
	HCB	559	3.70	99.34	815	2.31

Note: These tests, except for K/A01261444, involved no POHC feed to the kiln.

Of possibly more concern is the apparent ability of the system to respond differently to different levels of feed. The variation of DE_{AB} with feed rate might also be due to previously deposited materials being volatilized and contributing to the emission rates. The observed variation of DE_{A} with feed rate to the afterburner is shown for three compounds in Figure 17.

Close examination of the data presented in Table 41 reveals the surprising fact that when the input rate to the afterburner of a given species is large, the DE_{AB} is in the range of greater than 99%. On the other hand, when the input rate is small, the effective DE_{AB} decreases even to become negative in some cases, as shown on Figure 17 and Table 42.

At present it is believed that the decrease in DE_{AB} for these three compounds as their feed rate to the afterburner is decreased (at small feed rates), shown by the data on Figure 16, is the result of two different types of interactions within the afterburner. In the first case, holdup of POHC in the hot zone (presumably within the refractory material) could allow some release of residual chlorinated benzenes to the gas stream even when POHC is not fed to the kiln (as to the afterburner). The second process is the formation of these similar chlorinated benzenes from each other (essentially as PICs) during complex high-temperature chemical interactions within the afterburner. According to Table 39, TCB was regularly found as a PIC in the HCB tests, and HCB showed up in the stack or kiln transfer duct in sizeable amounts during the TCB tests. This effect, and the processes believed to be responsible, need to be explored in detail.

The last sample on Table 41 (K/A01261444) deserves further consideration. The hot zone sample from the kiln transfer duct indicated a feed rate to the afterburner of 559 μg/min of HCB. Comparison of this value to the 1.67 g/min (100 g/hr) HCB feed (Table 36) indicates that most of the observed destruction of HCB occurred in the kiln. Because of the long but unknown residence time in the kiln, however, the kiln DE cannot be determined with accuracy, so that the kiln of > 99.9% which would be calculated from the above data may not be representative of the actual situation.

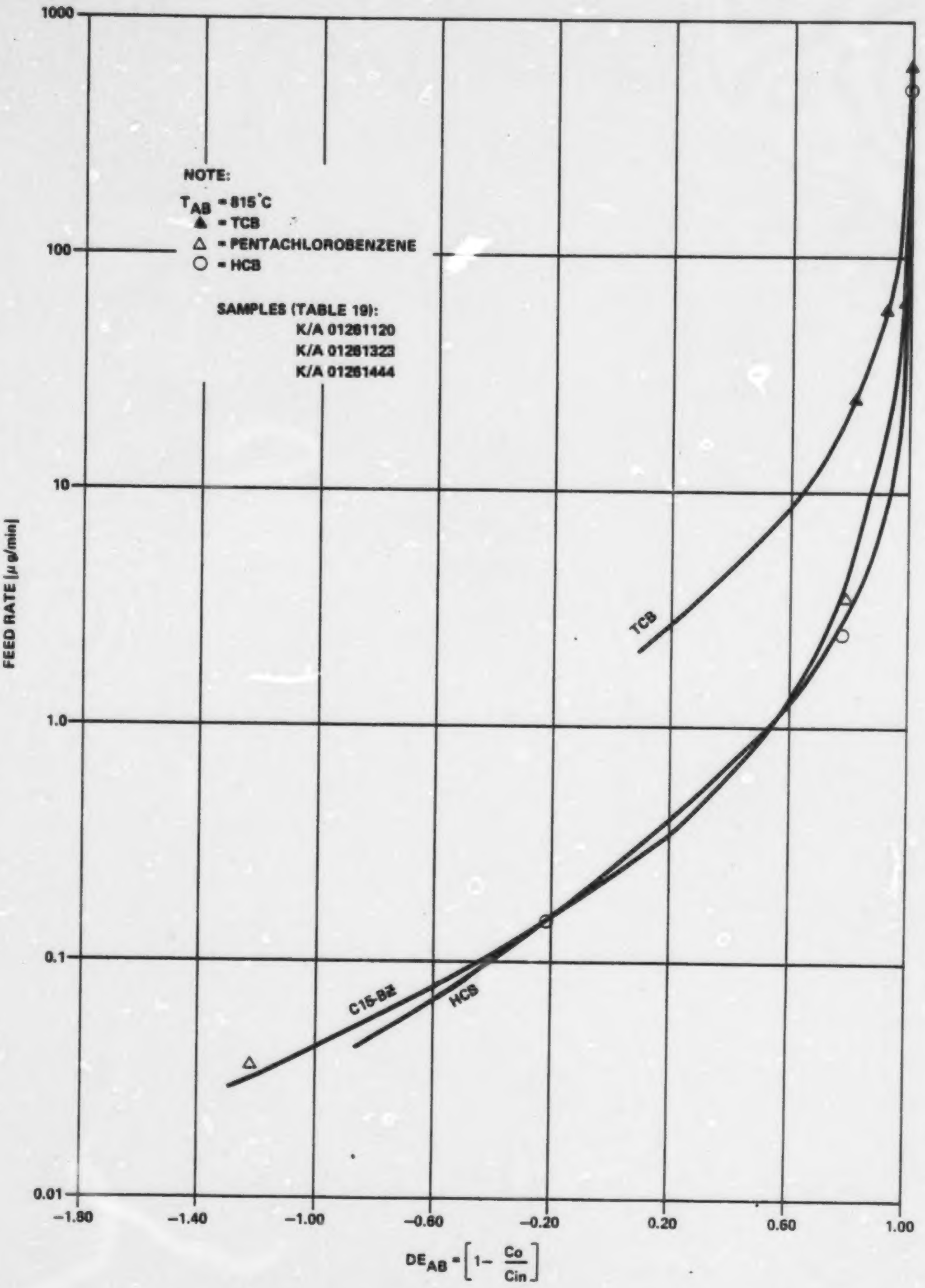


FIGURE 17 APPARENT VARIATION OF AFTERBURNER DESTRUCTION EFFICIENCY (DE) WITH POHC FEED RATE FOR HCB, PENTACHLOROBENZENE AND 1,2,4-TCB (AT LOW POHC FEED RATES).

TABLE 42. THE EFFECT OF POHC FEEDRATE ON DE_A

SAMPLE ID	POHC	A(o) (µg/min)	$A(t_r)$ (µg/min)	DE_A (%)
(K/A)01241050	TCB	130	1.22	99.06
(K/A)01241225	TCB	102	<0.75	99.26
(K/A)01241350	TCB	3200	2.59	99.92
(K/A)01261120	HCB	0.156	0.190	-21.79
(K/A)01261323	HCB	2.49	0.518	79.20
(K/A)01261444	HCB	559	3.70	99.34

TENTATIVE PIC IDENTIFIES

Gas Chromatographic Analysis

In addition to the tabulation of analytical findings in Table 39, it is of interest to note the complexity of the chromatograms of samples taken from the incinerator. In passing, it should be noted that the machine time per chromatogram was frequently as long as 90 or more minutes so that the GC using an automatic sampler was in continuous (24 hours a day, seven days a week) operation in order to deal with the samples derived from two experiments per week along with the necessary QA/QC and calibration samples.

The identity of each chemical substance reported below was established at a presumptive level of confidence using chromatographic methods. Confirmation of identity was then sought by analysis of selected sample extracts on several dissimilar columns (packed as well as bonded-phase) while different detectors were employed to meet specific needs for selectivity and sensitivity.

For example, analysis of a stack sample (S09221138-I_1, I_2, I_3*), taken during an experimental burn in which 1,2,4-trichlorobenzene was fed as POHC, identified the following chemical compounds:

1,3-dichlorobenzene
hexachloroethane
benzyl chloride
hexachloro-1,3-butadiene
1,2,4-trichlorobenzene
1,2,4,5-tetrachlorobenzene
pentachlorobenzene
hexachlorobenzene

This analysis was performed according to Method 8120 found in Test Methods for Evaluating Solid Waste - Physical/Chemical Methods (EPA/SW-846) with electron capture detection (ECD). When the analysis was repeated using a halogen-specific detector (HECD), six of the identifications above were confirmed as halogenated compounds while hexachloro-1,3-butadiene and 1,2,4,5-tetrachlorobenzene were shown not to be present in the sample extract. Thus the complementary use of ECD and HECD avoided the misidentification, in stack gas, of two possible PIC of 1,2,4-trichlorobenzene. The typical ECD results are shown in Figure 18 while those from HECD are shown in Figure 19.

For an additional example of chemical substance identification methods employed to date at the CRF, complementary chromatographic techniques. During

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*I_1, I_2, I_3 refer to the first, second, and third impingers, respectively.

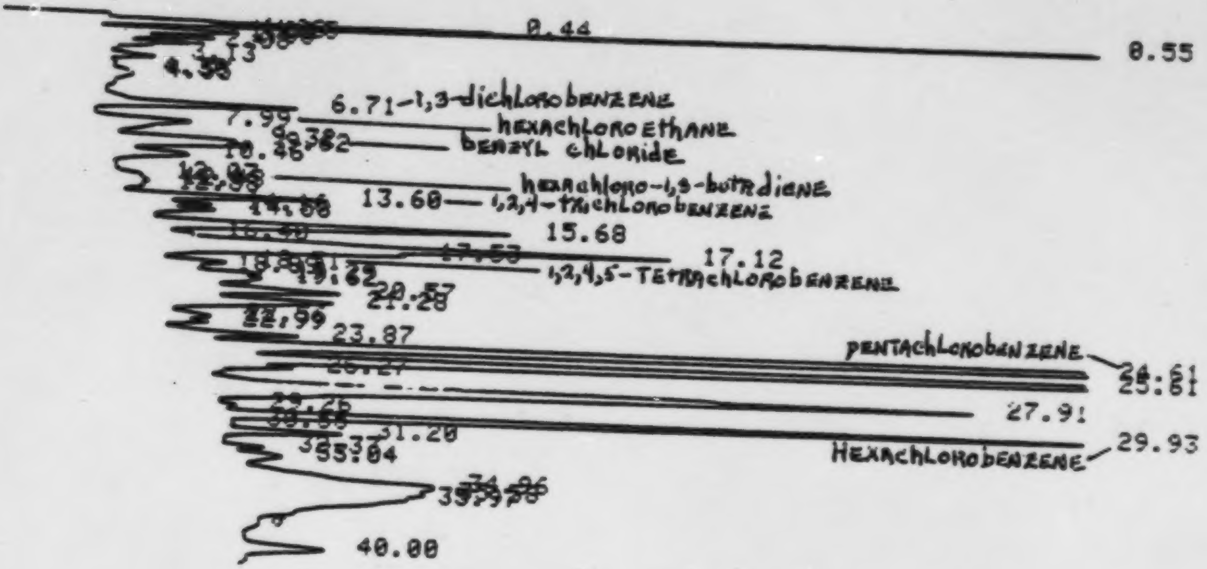

Figure 18

ECD gas chromatogram of sample #S09221138-I_1,I_2,I_3, showing presumptive identifications of several organic species.

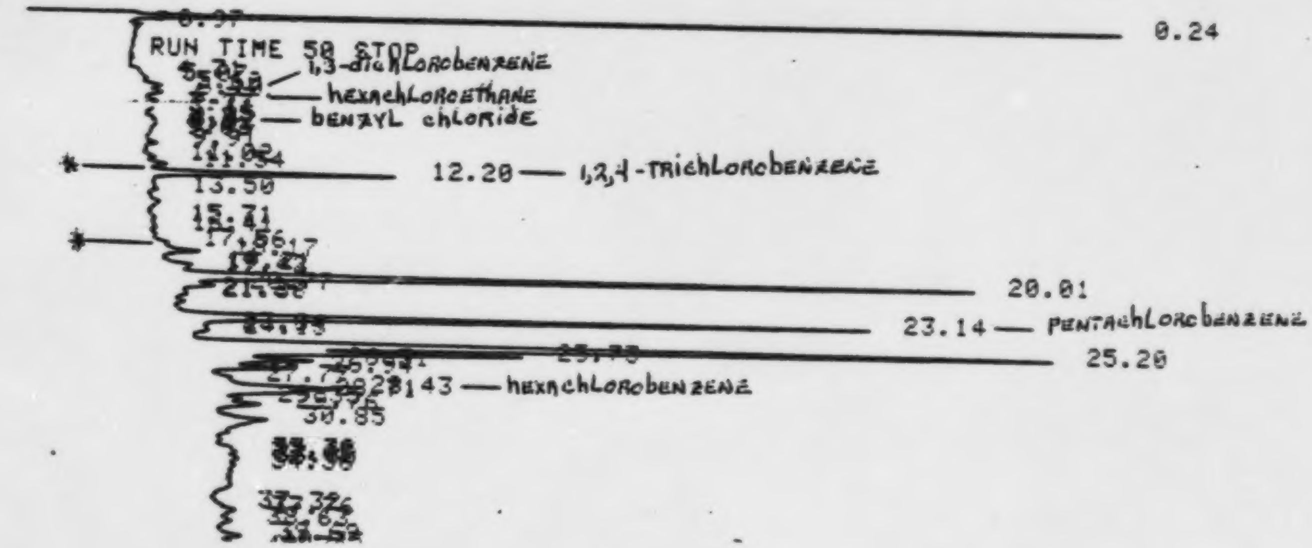

Figure 19
HECD gas chromatogram of sample #S09221138-I_1,I_2,I_3)
showing confirmation of several species presumptively identified
in Figure 18. Asterisks denote absence of
hexachloro-1,3-butadiene and 1,2,4,5-tetrachlorobenzene.

routine maintenance of the rotary kiln, after numerous 1,2,4-trichlorobenzene burns had been performed, the feed face of the kiln was opened. It was noted that the water-cooled feed lance had acquired a thin coating of soot which was removed for analysis (M12081213). This unique sample was chosen because: (1) it was thought to be a rich source of kiln-produced substances, the feed lance being in essence a "cold-finger" trap, and (2) a considerable body of literature exists as regards the typical composition and appropriate analytical strategy for such material. The sample was prepared according to Method 3550 of SW-846 and the extract was analyzed by chromatography on an Ultrabond column with flame ionization detector (FID). This rather complex chromatogram is displayed in Figure 20 while the corresponding presumptive compound identities are listed in Table 43. The sample extract prepared above was also analyzed by Method 8120 of SW-846 using ECD and this chromatogram is presented in Figure 21. Chemical species confirmed by this second analysis are marked with an asterisk in Table 43.

GC/MS Study of Sample M12081213 (Lance Scraping)

The extract from Sample M12081213 was analyzed (at Versar, Springfield, VA) on a Finnigan 4021 GC/MS with a 30m SPB-5 bonded phase capillary column. The data collected were initially processed using a reverse search technique for semivolatile hazardous substance list (HSL) compounds. Large peaks not identified by this process were then tentatively identified by comparing the mass spectra to the NBS library of 39,000 mass spectra. Estimated concentrations for the tentatively identified compounds were generated assuming a response factor of one compared to the nearest internal standard.

Sample M12081213 was a highly colored extract. It was run on the GC/MS without dilution. The results for the HSL compounds are presented in Table 44. The HSL compound present in the highest concentration was 1,2,4-trichlorobenzene. A number of PAHs were also present. The chromatogram from this sample is presented as Appendix B to this report.

This sample contained a number of peaks that were tentatively identified using library searches. The tentative identifications and estimated concentrations are presented in Table 45. Many of the library search compounds are PAHs and alkanes. The identifications on this table should be used with caution. PAHs of identical molecular weight but different structure typically produce spectra which are remarkably similar. Alkane spectra are

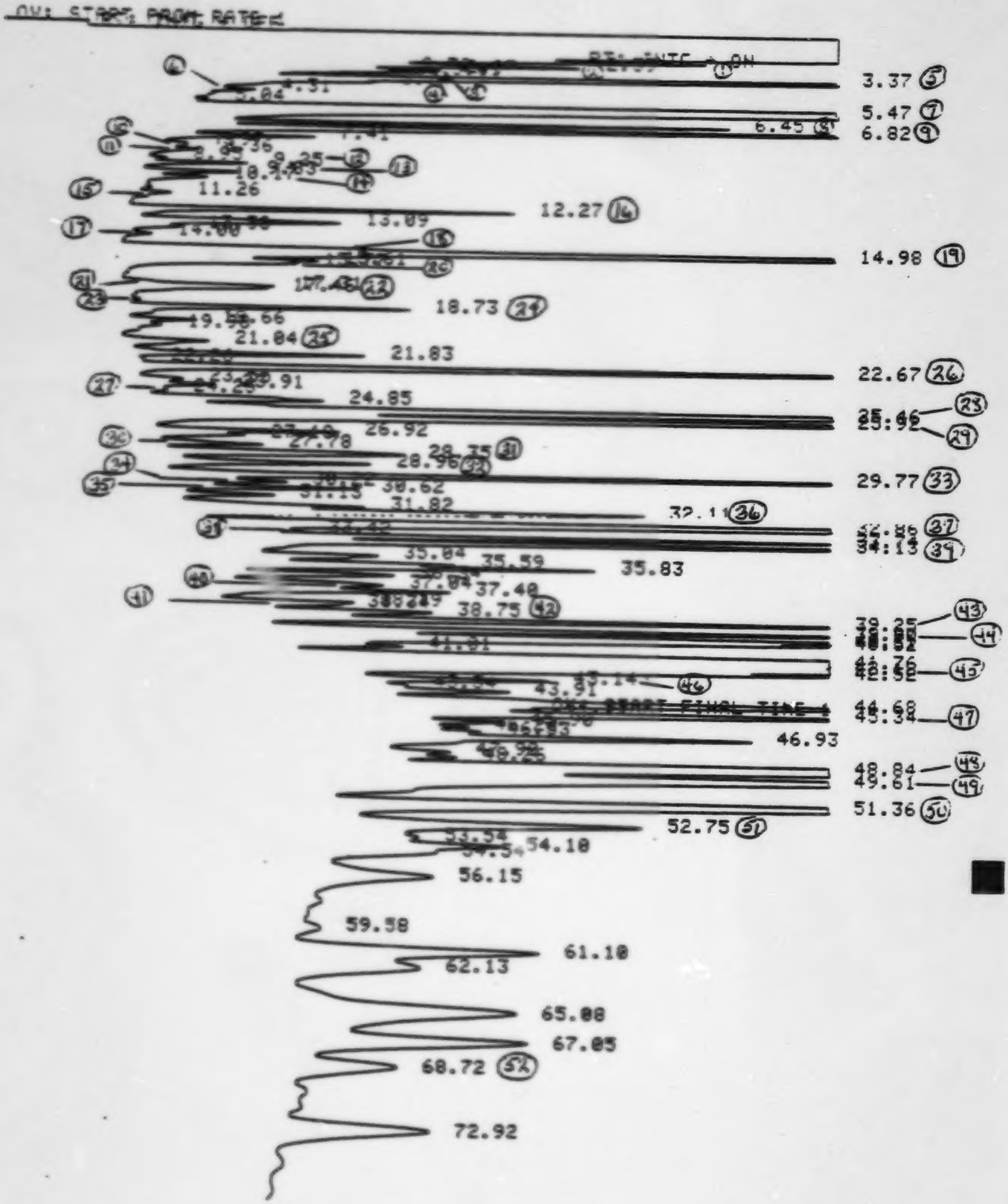

Figure 20

FID gas chromatogram of sample #M12081213 showing presumptive identification of many organic species found in feed lance soot. Numbered peaks are identified in Table 43.

TABLE 43. COMPOUNDS PRESUMPTIVELY IDENTIFIED IN SOOT FROM FEED LANCE-SAMPLE #M12081213

Peak No. in Figs.4&5	Identity	Peak No. in Figs. 3&4	Identity
1	1,3-dichlorobenzene*	25	diethyl phthalate
2	1,4-dichlorobenzene*		diphenylacetylene
	dodecane		eicosane
3	indene	26	2-chloro-1,4-naphthoquinone
4	1,2-dichlorobenzene*	27	diisopropyl phthalate
5	1,3,5-trichlorobenzene*		di-n-propyl phthalate
	benzyl chloride*	28	anthracene
6	tridecane		phenanthrene
7	1,2,4-trichlorobenzene*		docosane
8	octafluorobiphenyl=I.S.	29	9-fluorenone*
	α,α,α-trichlorotoluene	30	2-methylanthracene
	tetradecane		2,7-dichlorodibenzo-p-dioxin
9	1,2,3-trichlorobenzene*	31	1-methylphenanthrene
	naphthalene	32	xanthone
	α,α-dichlorotoluene	33	tetracosane
10	1,2,3,5-tetrachlorobenzene*	34	1-chloroanthracene*
11	1,2,4,5-tetrachlorobenzene	35	2-chloroanthracene
12	2-methylnaphthalene	36	anthraquinone*
13	1-methylnaphthalene	37	fluoranthene
14	p-chloroacetophenone		9,10-dimethylanthracene
15	hexadecane		9,10-dichloroanthrancene
16	biphenyl	38	hexacosane
17	heptadecane	39	pyrene
18	acenaphthene	40	octacosane
19	α-chloroacetophenone	41	1-chloroanthraquinone
20	acenaphthylene		bis-(2-ethylhexyl)-phthalate*
21	hexachlorobenzene*	42	benzilbutyl phthalate
22	dibenzofuran	43	9-phenylanthracene=I.S.
23	dibenzo-p-dioxin	44	benzo(c)phenathrene
24	fluorene	45	di-n-octyl phthalate
	nonadecane	46	1,8-dichloroanthraquinone
	dimethyl phthalate	47	benz(a)anthracene-7,12-dione*
		48	indeno[1,2,3-cd]pyrene
		49	octachlorodibenzo-p-dioxin*
		50	benzo(a)pyrene
			benzo(e)pyrene
		51	perylene
		52	1,2,3,4-dibenzanthracene

*Compound identity confirmed by complementary analysis shown in Figure 20.
I.S. denotes surrogate compound added to sample prior to processing for analysis.

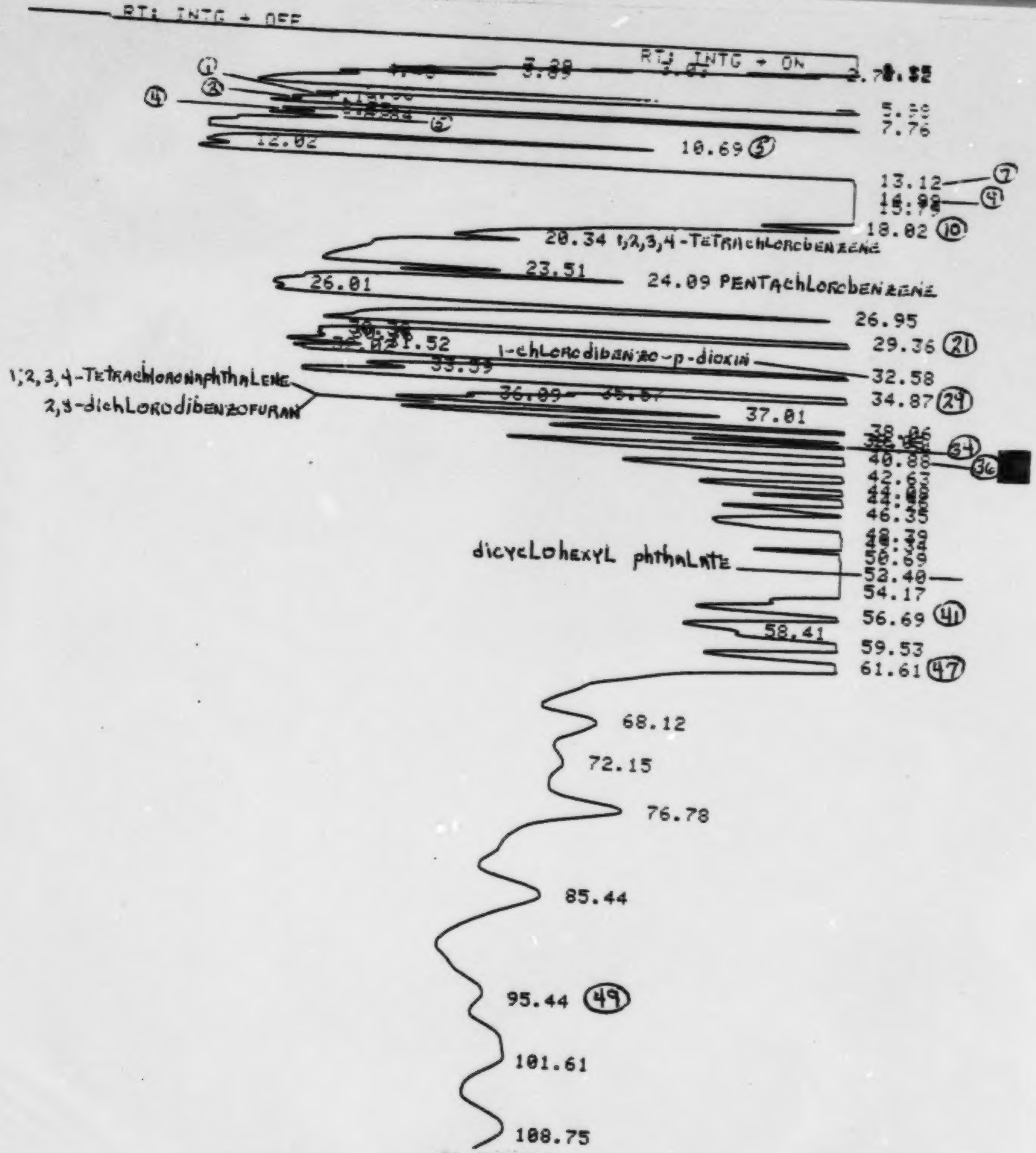

Figure 21

FID gas chromatogram of sample #M12081213 showing presumptive identification of many organic species found in feed lance soot. Numbered peaks are identified in Table 43.

TABLE 44. ORGANICS ANALYSIS DATA SHEET - SAMPLE NUMBER M12081213

SEMIVOLATILE COMPOUNDS

DATE ANALYZED: 5-8-84
CONC./DILUTION FACTOR: 1:1

PP #	CAS #		µg/ml	PP #	CAS #		µg/ml
(31A)	120-83-2	2,4-dichlorophenol		(55B)	91-20-3	naphthalene	15.9
(58A)	100-02-7	4-nitrophenol		(62B)	86-30-6	N-nitrosodiphenylamine	1.4
	534-52-1	4,6-dinitro-2-methylphenol		(66B)	117-81-7	bis(2-ethylhexyl)phthalate	1.7
(65A)	108-95-2	phenol	4.8	(68B)	84-74-2	di-n-butyl phthalate	1.3
	65-85-0	benzoic acid	32.4	(69B)	117-84-0	di-n-octyl phthalate	
	95-48-7	2-methylphenol	1.5	(70B)	84-66-2	diethyl phthalate	0.3
	108-39-4	4-methylphenol	2.4	(71B)	131-11-3	dimethyl phthalate	
	95-95-4	2,4,5-trichlorophenol		(72B)	56-55-3	benzo(a)anthracene	32.4
(1B)	83-32-9	acenaphthene		(73B)	50-32-8	benzo(a)pyrene	23.2
(5B)	92-87-5	benzidine		(74B)	205-99-2	benzo(b)fluoranthene	61.8
(8B)	120-82-1	1,2,4-trichlorobenzene	4.03	(75B)	207-08-9	benzo(k)fluoranthene	29.1
(9B)	118-74-1	hexachlorobenzene	1.7	(76B)	218-01-9	chrysene	50.1
(12B)	67-72-1	hexachloroethane		(77B)	208-96-8	acenaphthylene	4.8
(18B)	111-44-4	bis(2-chloroethyl)ether		(78B)	120-12-7	anthracene	16.5
(25B)	95-50-1	1,2-dichlorobenzene	1.3	(80B)	86-73-7	fluorene	7.5
(26B)	541-73-1	1,3-dichlorobenzene	1.1	(81B)	85-01-8	phenanthrene	49.3
(27B)	106-46-7	1,4-dichlorobenzene	1.4	(82B)	53-70-3	dibenzo(a,h)anthracene	9.8
(35B)	121-14-2	2,4-dinitrotoluene	1.8	(84B)	129-00-0	pyrene	22.9
(37B)	122-66-7	1,2-diphenylhydrazine	3.1		100-51-6	benzyl alcohol	2.6
(39B)	206-44-0	fluoranthene	44.9		106-47-8	4-chloroaniline	
	7005-72-3	4-chlorophenyl phenyl ether			132-64-9	dibenzofuran	2.2
(41B)	101-55-3	4-bromophenyl phenyl ether			91-57-6	2-methylnaphthalene	2.6

TABLE 45. GC/MS LIBRARY MATCHES - SAMPLE M12081213

COMPOUND	SCAN #1	CONCENTRAION (mg/ml)
4-methyl-1-pentene-3-ol	314	greater than 200
toluene	433	greater than 200
2-azido-2,3,3-trimethylbutane	515	3
ethyle benzene	553	9
xylene isomer	563	15
2,2,3,3-tetramethylhexane	595	31
1,1,2,2-tetrachloroethane	615	5
3-5-dimethyloctane	625	5
4-methyl-2-propyl-1-pentanol	636	14
benzaldehyde	674	65
decane	709	55
trimethylbenzene isomer	711	55
2,6-dimethylnonane	734	17
undecyl cyclohexane	752	9
2-hydroxy-benzaldehyde	768	5
2,4,6-trimethyloctane	814	7
1,2,3-trichlorobenzene	946	6
1,1'-biphenyl	1094	7
3-methyl-1, 1'-biphenyl	1180	5
1,1-bis-(1,2-ethanediyl)benzene	1211	54
diphenylmethanone	1295	6
E-1,1-bis-(1,2-ethenediyl)benzene	1352	25
9H-fluoren-9-one	1384	22
bis-chlorophenylmethane isomer	1401	5
bis-chlorophenylmethane isomer	1409	20
bis-chlorophenylmethane isomer	1443	5
1-phenyl-naphthalene	1462	7
2-phenyl-naphthalene	1537	21
9,10-anthracenedione	1543	8
1-(phenylmethylene)-1h-indene	1554	5
Unknown PAH	1619	9
11-H-benzo(a)fluorene	1694	10
7H-benz(de)anthracen-7-one	1796	13
benzo(c)phenanthrene	1829	16
benzo(ghi)fluoranthene	1834	16
1,2'-binaphthalene	1838	15

also usually difficult to interpret. The tentative identifications, therefore, probably contain a number of errors. For example, phenyl naphthalene isomers and phenylmethylene-1h-indene isomers have nearly identical spectra. Without authentic standards of these compounds, it is not possible to conclusively identify which compounds or isomers are present. It is, however, possible to conclude that PAHs of this molecular weight are present.

Some of the compounds may also be sampling artifacts. In our previous work with Tenax GC we have found benzaldehyde, benzoic acid, and 2-azido-2,3,3-trimethylbutane in blanks.

Comparison of GC and GC/MS Results

A comparison of the GC/MS results from the lance scrapings with the GC identifications of organics in the hot zones indicates that about 70 per cent of the compounds identified by GC alone were confirmed by the GC/MS results.

The confirmation results are summarized below:

Specific Compounds Confirmed by GC/MS	-	23
Alkane Class Compounds Confirmed	-	6
PAH Class Compounds Confirmed	-	8
Total Confirmed		37
GC Identification Refuted by GC/MS	-	4
Compounds Detected by GC but Not by GC/MS	-	12
Total Not Confirmed		16

The 12 compounds detected by GC but not GC/MS may have been present at levels below the detection limits of the GC/MS. In the scanning mode, the GC/MS detection limits can be as much as several orders of magnitude higher than those for the GC procedures used.

The alkanes and PAHs present complex spectra which are difficult to separate at the concentrations present in this sample. The results for alkanes and PAHs probably should be used as identification of the classes and not necessarily of specific compounds.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on the data and results from the chlorinated benzene test series reported in Section 3.

- The CRF incinerator can consistently produce the required DRE of 99.99% for surrogate POHCs HCB and 1,2,4-TCB in toluene solution.
- There was no apparent effect of residence time/temperature or feed rate on DRE over the ranges covered in the test series.
- DRE values for 1,2,4-TCB were higher than for HCB under comparable residence time/temperature conditions.
- Most of the thermal destruction occurred in the kiln.
- Engineering tests conducted without POHC feed always showed the presence in the system of the POHCs and PICs from previous tests with POHC feed.
- There is apparently a direct relationship between the DE of the afterburner (DE_{AB}) and the injection rate at very low injection rates.
- The behavior of the DE_{AB} at very low injection rates appears to result from a combination of POHC/PIC carryover (holdup) from previous burns plus PIC formation in the afterburner.
- A number of PICs, notably polyaromatic hydrocarbons (PAHs) and other chlorinated benzenes, were formed in the tests with HCB/toluene or TCB/toluene feed. No dioxins or dibenzofurans were identified in any of the analyses for PICs.
- Agreement between GC/MS and multidetector GC identification of PICs was very good.
- The procedures implemented for hot zone sampling at the CRF appear to yield consistent results in terms of POHC/PIC determinations.

Recommendations derived from the work reported in Section 3 include:

- The richness of the analytical findings that derive from the ability to sample the high temperature zones, coupled with the variety of PICs identified, suggest that further work on surrogate POHCs and made-up waste simulants would be beneficial to the more complete understanding of the incineration process.
- The behavior of DE_{AB} at very low injection rates should be studied in detail, particularly with respect to the holdup of organic materials in the hot zones and POHC/PIC interactions in the afterburner.
- Attempts should be made to determine mixing characteristics in the afterburner and the effects of such mixing on the temperature distribution, residence time and performance of the incinerator.
- The turndown ratio of the burners currently installed limits the available range of feed rate; the burners need to be upgraded.

SECTION 4

FAILURE MODE TESTS

AFTERBURNER FLAME OUT SIMULATION

The tests performed on 11/9/83 and 11/11/83 were used to study simulated flame out conditions in the afterburner. The first test, with propane fuel only (no toluene or chlorinated benzene), was used to establish conditions for a test using TCB/toluene feed and to monitor carbon monoxide levels during flame out. The conditions used were such that the kiln temperature was 760°C (1400°F) and that of the afterburner 871°C (1600°F). In order to simulate flame out conditions, the burner on the afterburner was shut off periodically for 2 minutes out of every 15 minutes. This cycle was repeated a total of 10 times. The shut off involved only the propane; the combustion air flow was maintained during the shut off periods.

The composition of the combustion gases was monitored on a continuous basis during these experiments. Figure 22 represents the excursions in CO that were observed during the burner off periods. The base line in Figure 22 represents the observation that, under normal operating conditions, the CRF system consistently indicates CO levels below 1 ppm (the least count on the CO monitor). The very large excursions in CO level during fire up or shut down periods are, at present, unexplained.

The effect on CO_2 concentration is shown on the (smoothed) plot in Figure 23. One may then combine the data in Figures 22 and 23 to estimate the combustion efficiency at various times in the operational cycle. These calculations are shown graphically in Figure 24. The top line represents the estimate that the normal combustion efficiency is at least 99.99% (based on the least count sensitivity of the CO monitor).

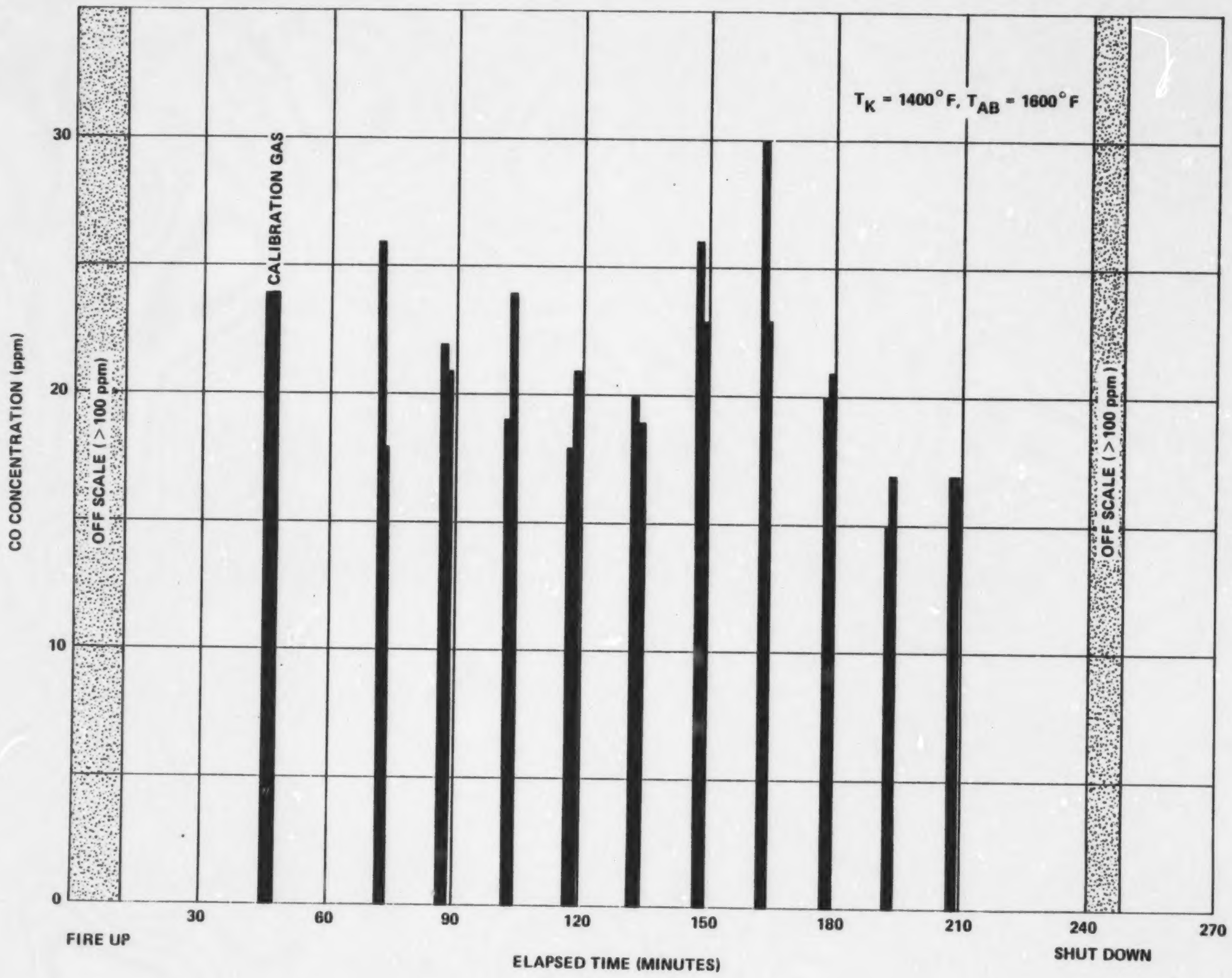

FIGURE 22. CO (STACK) CONCENTRATION VARIATION DURING SIMULATED FLAME OUT TESTS (11/9/83)

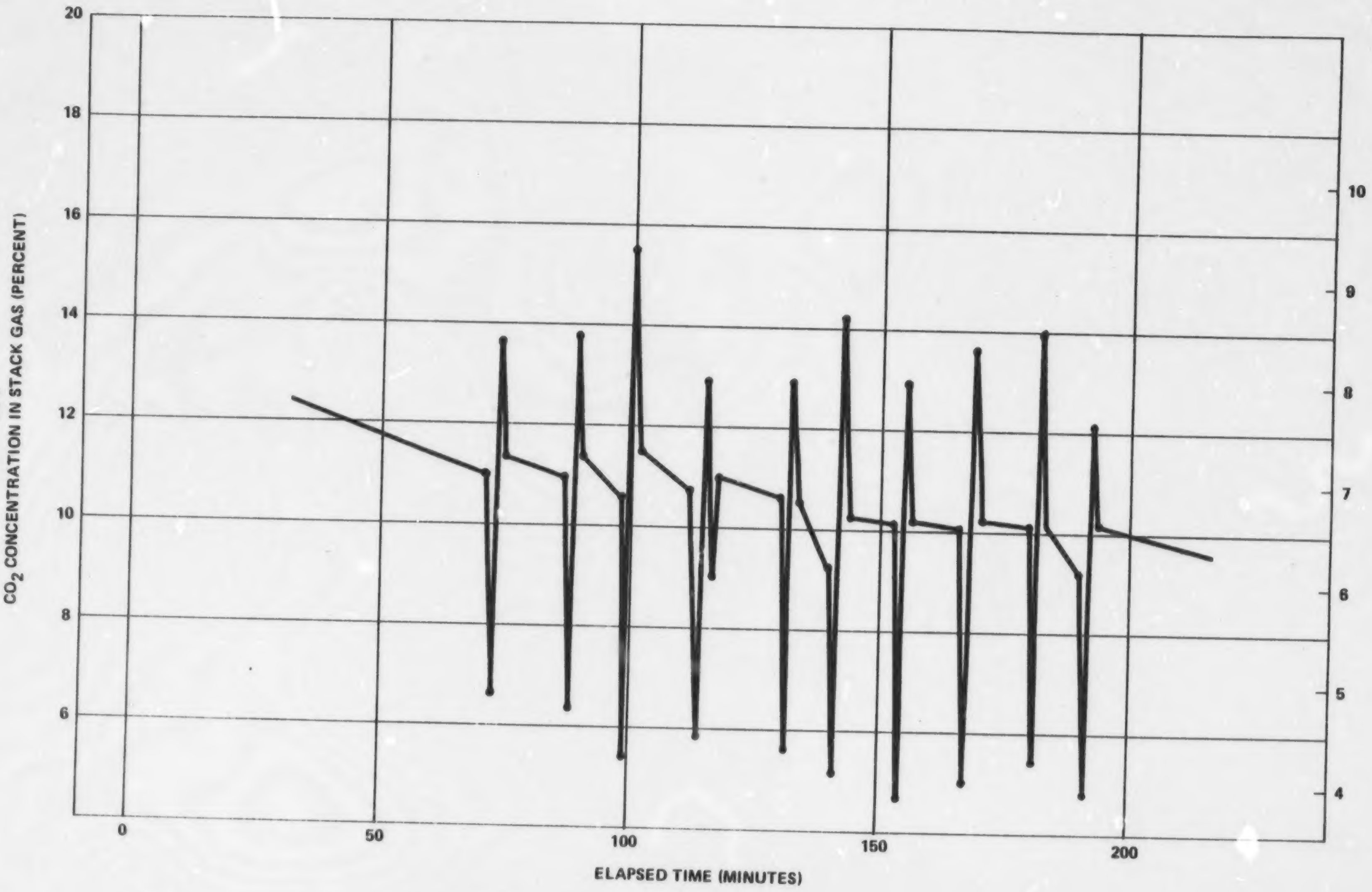

FIGURE 23. CO_2 CONCENTRATION (STACK) DURING AB "FLAME OUT" SIMULATION (DATA SMOOTHED TO ELIMINATE NOISE)

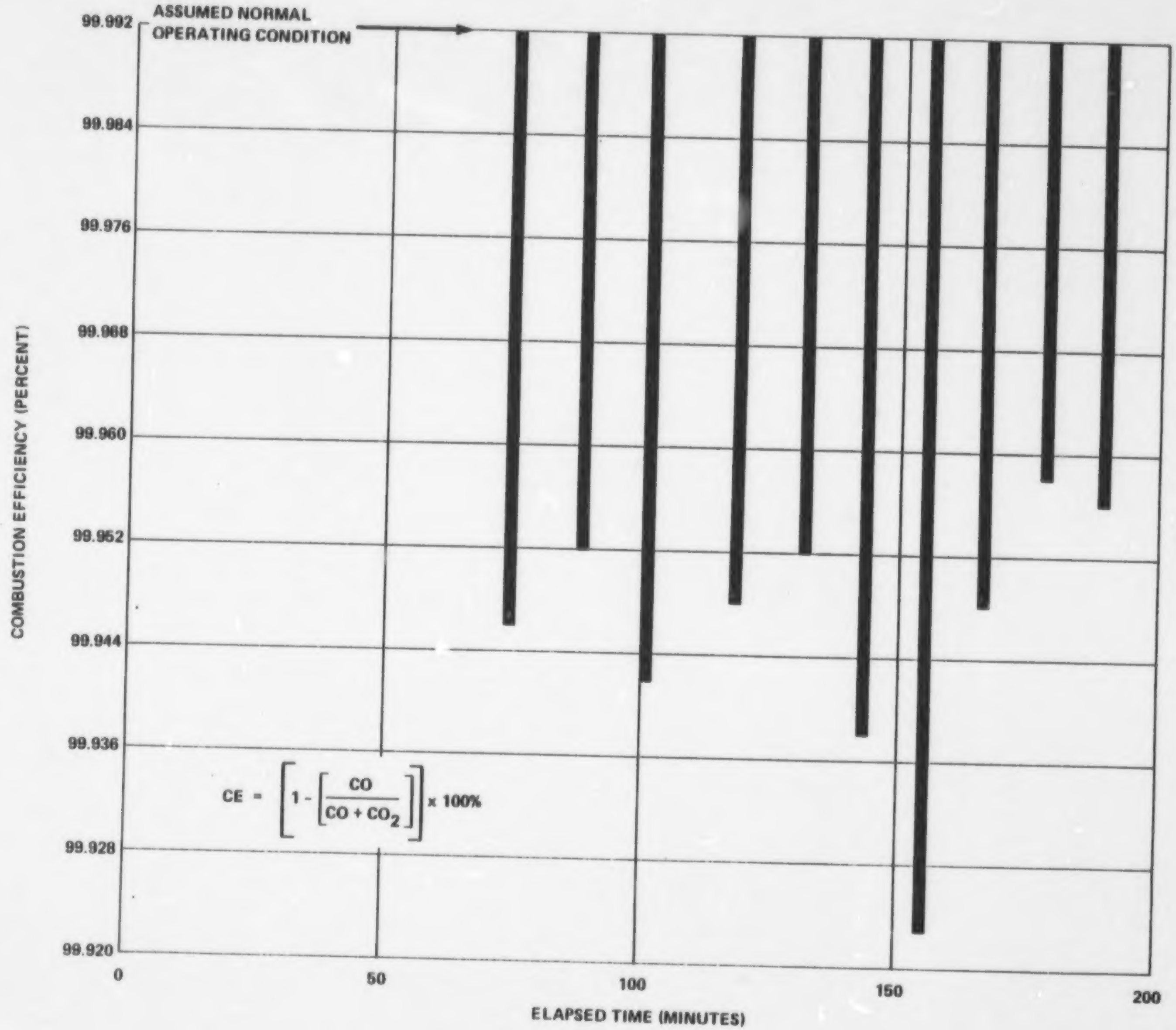

FIGURE 24. EFFECT OF 2-MINUTE AFTERBURNER FLAME OUTS ON COMBUSTION EFFICIENCY (CE)

The above flame out conditions were reproduced during the test on 11/11/83, the only significant difference being that on 11/11/83, there was POHC feed to the kiln of 100 g/hr 1,2,4-TCB (plus 2.8 lit/hr toluene). Analytical data for the two test days under periodic afterburner flame out conditions are presented in Table 46 (from Table 39).

According to Table 46, some of the PICs were observed at higher concentration with the TCB feed; these include benzyl chloride and 1,2,4,5-tetrachlorobenzene. The other PICs that were observed behaved similarly except di-n-butyl phthalate which appeared higher with no TCB feed. HCB (CL6-BZ on Table 46) was higher in the kiln exit gas with TCB feed but below detection in all cases for the afterburner exit gas. The levels of 1,2,4-TCB were mostly below detection even with TCB feed; DRE values for the system based on TCB were well above 99.99%. It it thus concluded that perturbation of the system by the simulated afterburner flame out failure mode was not significant.

KILN FAILURE MODE TESTS

The second type of failure simulation test was carried out in the kiln. In this case, it was required that the afterburner be operated at the highest possible temperature with the kiln at 1500°F. When steady state conditions had been reached, the kiln burner was shut down (primary combustion air remained at normal flame-on level). The typical kiln gas cooling rate was as shown in Figure 25. It is noted that the time required to cool 50°F was approximately 25 seconds. With this information, the experimental design was as shown in Table 47; the test was performed on 11/18/83.

The system was carried through three heating/cooling cycles (with feed only) extending for the time required for the temperature (gas) to fall through a 55°F range three times. Kiln transfer line sampling was carried out during each cycle only over the desired 50°F interval. Feed was initiated when the kiln temperature was 5-10° above upper set point and discontinued at 5-10° below bottom set point. Sampling was initiated at the upper set point and terminated at the lower set point at a sampling rate of approximately 12 l/m.

TABLE 46. HOT ZONE ANALYTICAL RESULTS FOR AFTERBURNER FLAME OUT FAILURE MODE SIMULATION TESTS

(Spikes have been omitted)

Sample I.D. Number	No POHC Feed				100 g/hr HCB Feed			
	K1109-1008	A1109-1008	K1109-1136	A1109-1136	K1111-1039	A1111-1039	K1111-1210	A1111-1210
Analyte* (µg/min)								
CL5-EANE	<0.055	0.371	<0.055	<0.098	<0.055	<0.098	<0.055	<0.098
1,3-DCBZ(m)	<0.77	<1.4	<0.77	<1.4	0.735	<1.4	0.142	<1.4
1,4-DCBZ(p)	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0	<1.7	<3.0
CL6-EANE	0.482	<0.77	<0.43	<0.77	<0.43	<0.77	<0.43	<0.77
1,2-DCBZ(0)	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2	<0.66	<1.2
BENZYL CL	<0.67	<1.2	<0.67	<1.2	38.8	21.3	39.1	19.5
1,3,5-TCBZ	<0.29	<0.52	<0.29	<0.52	0.361	<0.52	<0.29	<0.52
HC-1,3-BD	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12	<0.067	<0.12
1,2,4-TCBZ	<0.42	<0.75	<0.42	<0.75	0.976	<0.75	<0.42	<0.75
1,2,4,5-TCBZ	<0.072	<0.13	<0.072	<0.13	1.98	12.2	1.99	11.2
1,2,3,4-TCBZ	<0.041	<0.072	<0.041	<0.072	0.912	<0.072	0.0644	<0.072
2-CL-NAPHTH	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3	<1.9	<3.3
CL6-BZ	<0.086	<0.15	<0.086	<0.15	0.796	<0.15	0.223	<0.15
ALPHA-BHC	0.392	0.361	<0.17	<0.30	0.793	0.308	0.489	<0.30
GAMMA-BHC	0.681	<0.55	0.705	<0.55	<0.31	<0.55	<0.31	<0.55
1,2,3-4-TCNAPHTH	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61	<0.34	<0.61
DEP	66.5	89.2	36.9	87.9	105	67.8	52.8	41.7
DNBP	477	501	465	492	36.9	72.2	26.0	44.5
BUBZP	10.1	16.7	9.93	16.3	5.88	4.10	5.92	3.76

*Identity of analytes shown on Table 38.

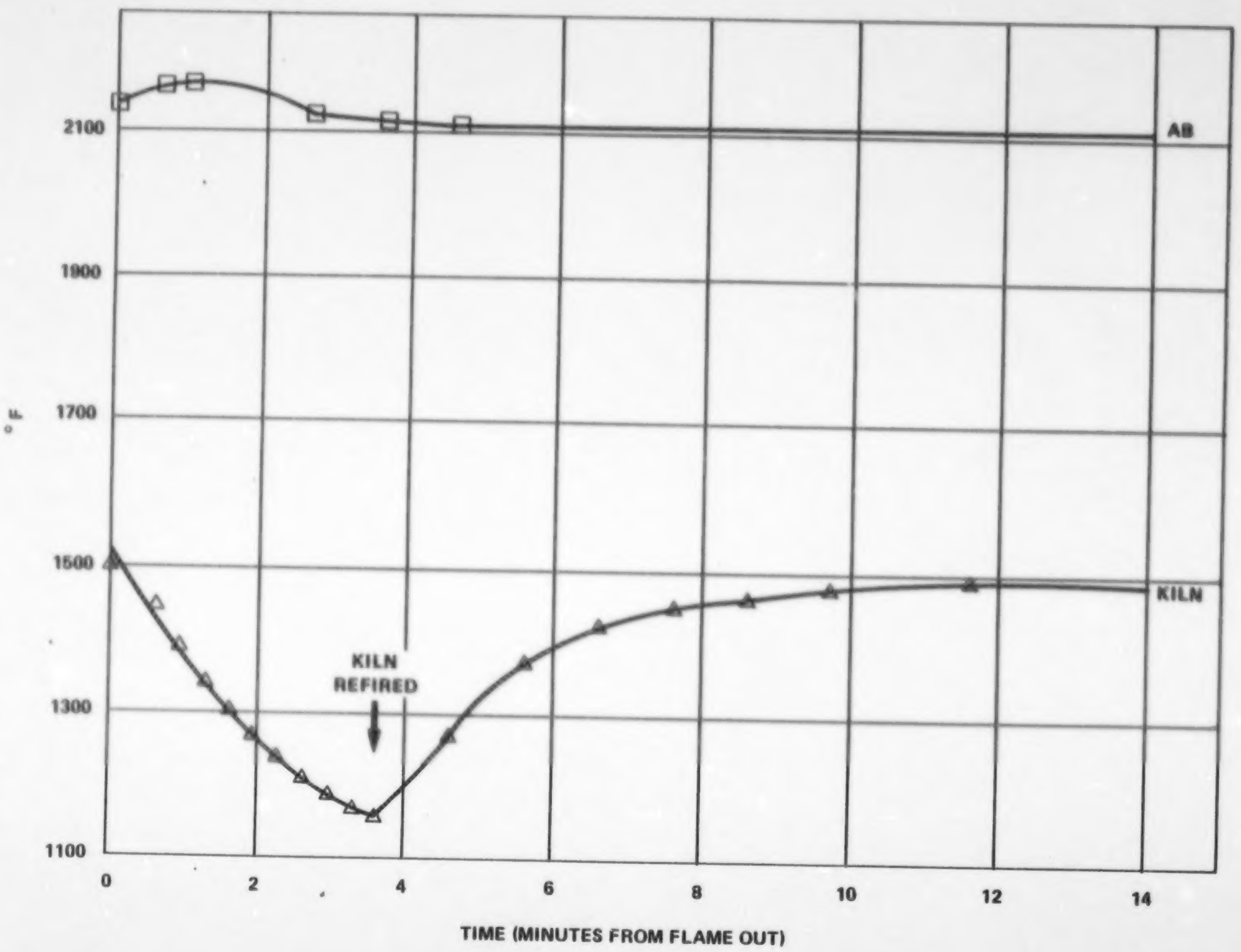

FIGURE 25. TYPICAL RESPONSE OF KILN AND AFTERBURNER TEMPERATURES TO DELIBERATE KILN FLAME OUT

TABLE 47. KILN FLAMEOUT STUDY

KILN TEMP.	FEED RATE*	SAMPLING RATE	FLAME
1500°	-0-	-0-	on
1500°	-0-	-0-	off
1455°	4000 gm/hr	-0-	off
1450°	4000 gm/hr	12 l/min	off
1400°	4000 gm/hr	12 l/min	off
1399°	-0-	-0-	on
1500°	-0-	-0-	on
1500°	-0-	-0-	off
1355°	4000 gm/hr	-0-	off
1350°	4000 gm/hr	12 l/min	off
1300°	4000 gm/hr	12 l/min	off
1299°	-0-	-0-	on
1500°	-0-	-0-	on
1500°	-0-	-0-	off
1255°	4000 gm/hr	-0-	off
1250°	4000 gm/hr	12 l/min	off
1200°	4000 gm/hr	12 l/min	off
1199°	-0-	-0-	on

*1,2,4-TCB

In the lowest interval (1250-1200°F), significant quantities of 1,2,4-TCB were found in the kiln transfer line. As a corollary to this, there were also large quantities of soot which resulted in poor performance of the kiln burner in subsequent experiments. This effect resulted in the need to remove and clean the kiln burner assembly.

The results of the kiln burner flameout experiment are summarized in Table 48 (abstracted from Table 39). The feed rate of 1,2,4-TCB was equivalent to 4000 gms/hr (no carrier and no propane feed during the sampling period). Several conclusions may be drawn from Table 48:

- The fact that the only feed was 1,2,4-TCB strongly indicates that the other compounds listed in Table 48 are PICs of 1,2,4-TCB.
- In spite of the (comparatively) high feed levels to the afterburner, the emission rates are mostly below detection levels.
- The DRE of the system, taking the feed to be $\left(\frac{4000}{3600} \times 25 \times 3\right) = 83.3$ gms and the total emissions to be (7.59 µg/min x 23 min) = 174.6 µg was 99.9998%, confirming the lack of dependence of DRE on feed rate from 100 gm/hr to 4000 gm/hr.
- The loss of the kiln burner will not of itself result in the system being out of compliance.
- The reported phthalates are apparently formed even in the absence of toluene (the TCB feed was neat) and presumably even in the absence of propane feed and with sampling only in the absence of a flame (as indicated on Table 46).
- It is not possible to predict the observed DE_K on the basis of first order kinetics since neither the effective temperature nor the effective residence time is known.

TABLE 48. KILN FAILURE EXPERIMENTS – HOT ZONE ANALYTICAL RESULTS

ANALYTE*	K11181113 (μg/min)	K11181125 (μg/min)	K11181136 (μg/min)	A11181113 (μg/min)
1,2-DCBZ(o)	<0.66	<0.66	536	<1.2
1,3,5-TCBZ	<0.29	<0.29	1500	<0.52
HC-1,3-BD	<0.067	<0.067	476	<0.12
1,2,4-TCBZ**	210	682	884000	7.59
1,2,3,4-TCBZ	<0.041	<0.041	7810	<0.072
C15-BZ	0.505	5.06	57200	0.569
C16-BZ	<0.086	<0.086	51300	0.947
1,2,3,4-TCNAPHTH	<0.34	<0.34	2980	<0.61
DEP	<0.22	<0.22	2390	267
DNBP	<0.87	<0.87	37100	3400
BUBZP	51.3	231	5580	24.1
T_K (°C)	815-788	760-732	704-677	815-788
T_A (°C)	1093	1093	1093	1093

* Analyte designations are shown on Table 38.

**1,2,4-TCBZ was the POHC introduced at a rate equivalent to 4000 gm/hr.

SECTION 5

FLOWRATE AND RESIDENCE TIME MEASUREMENT BY HELIUM DILUTION

INTRODUCTION

The injection of helium at a constant, known flow rate into the rotary kiln, and the subsequent sampling and analysis for helium concentration in process gas samples withdrawn from downstream locations, is a technique utilized at the CRF for determining volumetric flowrates, linear velocities, and superficial residence times for the combustion gases in the hot incineration zones and in the exhaust stack. Additionally, the instantaneous injection of a pulse of helium, followed by the sampling and analysis for helium concentration variations with time at downstream locations, provides for a measure of the distribution of residence times, important in explaining experimentally-determined destruction efficiencies in pilot-scale (and larger) incinerators.

STEADY-STATE FLOWRATE MEASUREMENTS USING HELIUM TRACER GAS

To quantitatively apply the concentration results of hot-zone sampling and analysis to destruction efficiency calculations, measurements of combustion gas flowrates must also be made. Flowrates of hot and frequently-corrosive gases in the kiln transfer duct and in the afterburner exhaust duct are difficult to measure, and the difficulty is compounded by the sharp turns and rapidly-changing cross-sections of these ducts.

The flowrate measurements in hot combustion zones are accomplished at the CRF using a helium tracer technique. A known steady quantity of helium, q standard l/min, is injected into the kiln at a point sufficiently far upstream of the kiln transfer duct and the afterburner exhaust duct to assure adequate mixing of the tracer with the combustion gases. Then if the volumetric flowrate of combustion gas at either of these points is Q standard l/min, the concentration of helium, C, would be $C = \frac{q}{q+Q}$. Since q is known, the determintion of the helium concentration C via sampling and subsequent analysis of the combustion gases provides a measure of Q:

$$Q = \frac{q(1-C)}{C}.$$

Helium was selected as the tracer gas because it meets the following desirable property criteria:

- should be thermally stable under the most hostile conditions.
- should not be a component of any waste likely to be a research candidate.
- should be readily detectable at reasonably low concentrations.
- should be readily available.
- should be a low boiling point material so as to simplify the injection, measurement, and control of the injection rate.
- must not be hazardous when emitted from the stack.
- should have low aqueous solubility so as to extend the measurement to include the stack measurements.

Clearly, since the requirement that the tracer not be hazardous when emitted from the stack, radioactive tracers are ruled out. The alternative is to use one of the noble gases with helium as the obvious choice since the thermal conductivity detector responds well to the high thermal conductivity of helium. [Note: For those incinerators using natural gas as auxiliary fuel, the use of helium as a tractor is less propitious since some natural gas contains appreciable concentrations of helium.]

The helium tracer system at CRF is shown schematically in Figure 26. Ultrapure helium is injected into the kiln feed face at a standard rate of 5 l/min controlled by a Tylan Model RO-20A flow controller. This injection location was selected to ensure that the tracer would see the same average mixing processes as do the volatile components of the test waste. Sampling

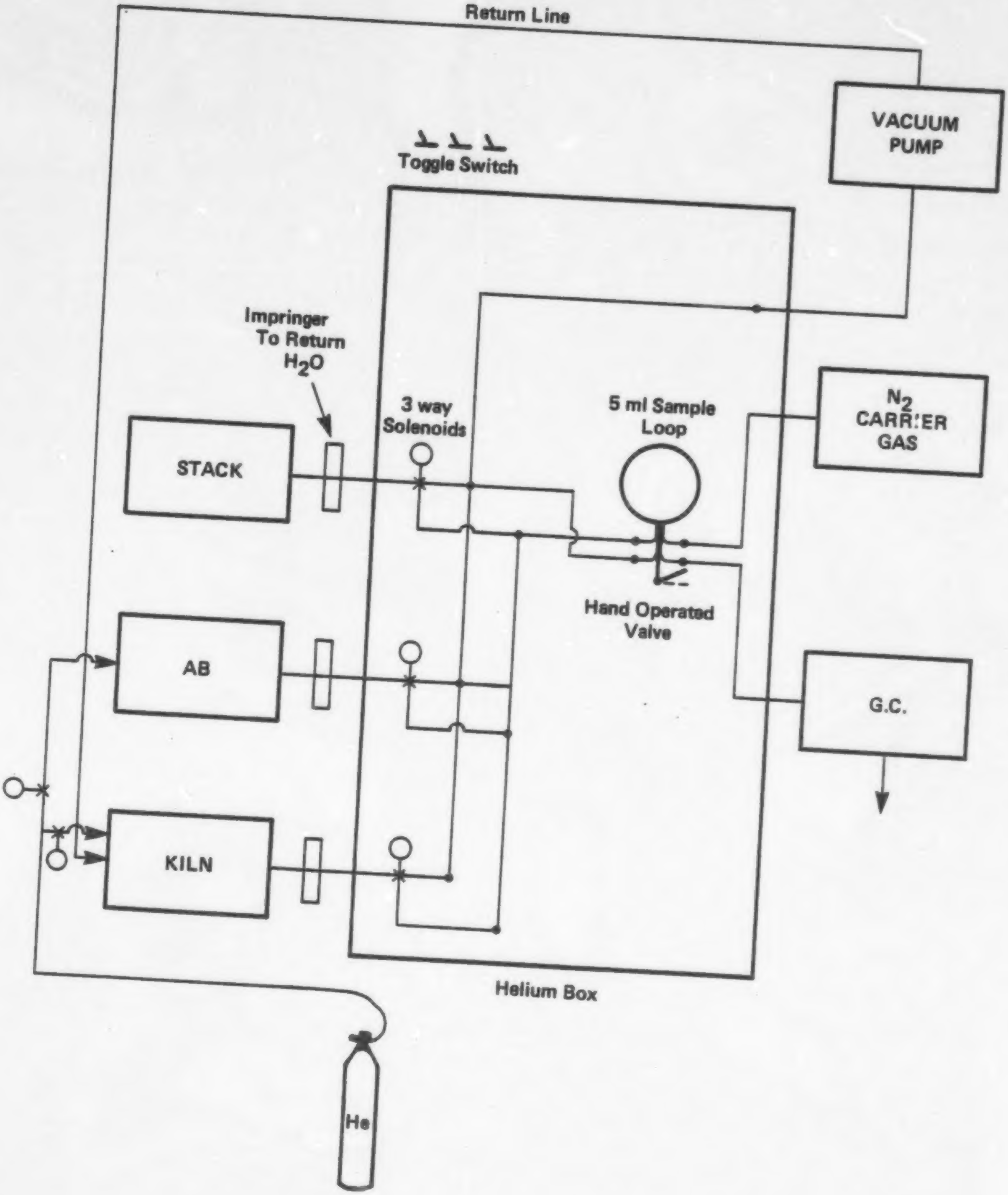
Return Line
VACUUM PUMP
Toggle Switch
Impringer To Return H_2O
3 way Solenoids
5 ml Sample Loop
N_2 CARRIER GAS
STACK
Hand Operated Valve
AB
G.C.
KILN
Helium Box
He

FIGURE 26. HELIUM DILUTION SYSTEM

ports are fixed on the kiln transfer duct, the afterburner exhaust duct, and on the stack. Sampling, at the rate of 2 dslm, is accomplished through fixed stainless steel sampling probes at each of the three sampling sites. The extracted sample is transferred through a heat-traced Teflon sampling line to the sample conditioning system where the sample is cooled and water removed, prior to its introduction into the sampling loop of a GOW MAC Model 69-570 gas chromatograph. The column is a 6' x 1/4" stainless tube packed with 80/100 molecular sieve 5A, operated at 150°C with nitrogen carrier gas flow of 20ml/min with detection using a thermal conductivity detector. Calibration is frequent using dry nitrogen containing known concentrations of helium. The method is further routinely calibrated against a standard pitot scan of the stack. Stack velocity measurements are automatic at 30 minute intervals.

Since moisture is removed from each gas sample prior to helium analysis, the results are in terms of dry (moisture-free) volumetric flowrate. The moisture in each gas sample is collected over a known time interval and weighed, converted to the water vapor standard volume, and added to the dry volumetric flowrate to provide the total volumetric flowrate in standard liters per minute. Actual volumetric flowrate is determined using the combustion gas temperature measurement at the appropriate sampling point. Linear velocity is then derived with the use of the known duct cross-sectional area. Mass flowrates of combustion gases are calculated from the standard volumetric flowrates, with the aid of carbon dioxide and oxygen concentration measurements which (in conjunction with the water vapor data) determine the overall gas composition and thus the average molecular weight.

The superficial combustion gas residence times in each of the combustion chambers and in the transfer and exhaust ducts are calculated from the actual volumetric flowrates and the known interval volume of each chamber or duct.

Section 2 of this report contains the raw data for helium concentration measurements and for condensed water collected from combustion gas samples, the data reduction procedures and algorithms, and the reduced data for volumetric and linear flowrates and for superficial residence times.

RESIDENCE TIME DISTRIBUTION AND ITS IMPORTANCE TO DESTRUCTION EFFICIENCY

The superficial residence time t_r for combustion gases in a chamber (either the kiln, the afterburner, or either of the connecting ducts) is simply defined as the internal volume of the chamber divided by the volumetric flowrate ($t_r - V/Q$). Only under ideal plug flow conditions does all of the combustion gas experience precisely the same residence time (the superficial residence time). Such ideal conditions may be approximated in laboratory-scale experiments in a tubular reactor.

In pilot-scale and larger incinerators, the degree of axial mixing and/or diffusion becomes appreciable, resulting in departures from plug flow. Instead of a uniform residence time for all portions of the combustion gas, a residence time distribution (RTD) exists, such that some of the gas spends a much shorter time than t_r in the chamber. An extreme case is where the chamber is approximated by a completely-stirred reactor model, such that some entering molecules of waste feed could quickly exit from the chamber with very little (relative to t_r) residence time for reaction/destruction. This becomes important when one considers the RCRA regulations requiring that not more than 0.01% of the injected POHC appear in the emissions from an incinerator. It thus becomes of interest to determine the extent to which some molecules might pass through the chamber in time much less than t_r as defined above.

To quantitatively illustrate how sensitive destruction efficiency (DE) might be to a realistic residence time distribution (RTD) in the CRF afterburner, the following calculations were performed assuming the hexachlorobenzene (HCB) is the POHC to be destroyed. If pseudo first-order kinetics hold, then

$$1\text{-DE} = \frac{C}{C_o} = \exp\,[-kt] = \exp\,[-At\,\exp(-E/RT)] \qquad (1)$$

where t is the residence time, k is the reaction rate constant, A the Arrhenius factor, E the activation energy, R the universal gas constant and T the absolute temperature. For HCB, $A = 2.2 \times 10^{-2}$ sec^{-1} and $E = 39$ kcal/gm mole.

One model that has successfully been used in the past to describe the RTD in a complex system such as the CRF afterburner is that of three ideal reactors in series: a plug-flow reactor followed by two identical completely-stirred reactors. If f(t) is a probability function, that is, f(t)dt is the probability that a given molecule will experience a residence time lying in the interval t to t+dt, then

$$\int_{0}^{\infty} f(t)dt = 1,$$

and the aggregate residence time $\hat{t}$ is

$$\hat{t} = \int_{0}^{\infty} tf(t)dt. \qquad (2)$$

The lower integration limit b is the shortest possible time, and is equivalent to V/Q in the first (the plug flow) reactor of the three ideal reactors in series. Then the boundary conditions are

$$f(t \leq b) = 0$$

$$f(t \rightarrow \infty) = 0.$$

The utility of f(t) derives from the fact that the expectation (or weighted average value) of a parameter is given by

$$<g(t)> \equiv \int_{b}^{\infty} g(t)f(t)dt \qquad (3)$$

According to Levenspiel,(1) for the three ideal reactors in series,

$$f(t) = \left[\frac{2}{\hat{t}-b}\right]^2 (t-b) \exp\left[-\frac{2}{\hat{t}}(t-b)\right] \qquad (4)$$

Letting $< \frac{C}{C_o} >$ from Equation (1) be the expectation value <g(t)> in Equation 3,

$$< \frac{C}{C_o} > = \int_{b}^{\infty} < \frac{C}{C_o} > f(t)dt = - \int_{b}^{\infty} \exp(-kt)f(t)dt$$

which on substitution, integration and evaluation at the limits yields

$$1 - DE = < \frac{C}{C} > = \left[\frac{2}{2+k\hat{t}}\right]^2 \exp[-bk]. \qquad (5)$$

---

(1) Levenspiel, O. "Chemical Reaction Engineering", 2nd Edition, pp 290, Wiley, N.Y., 1962.

For predictive use of this model, the superficial residence time $t_r = V/Q$ for the entire afterburner chamber may be used for t in Equation (5).

Equation (5) then permits the calculation of a predicted destruction efficiency (DE) for the CRF afterburner, using the three-reactor-in-series composite model (the last two being completely-stirred reactors), from a superficial residence time t_r (used as a value for t), a minimum residence time b, and a first-order rate constant k. This predictive method is based upon a distribution of residence times consistent with segments of the combustion chamber permitting some fraction of the molecules to exit from those segments almost immediately.

Conversely, Equation (1) permits DE to be predicted from the same superficial residence time t_r and the same first-order rate constant k, but under the ideal plug-flow condition that all molecules experience the same residence time t_r in the chamber.

Table 49 is a comparison of DE values calculated both ways for the same values of t_r and k. It is apparent that the composite model (with its implicit distribution of residence times) approaches an afterburner DE of 0.9999 much more slowly than does the ideal plug-flow model.

MEASUREMENT OF RESIDENCE TIME DISTRIBUTION USING HELIUM TRACER GAS

The importance of the residence time distribution (RTD) to destruction efficiency was discussed in the preceding subsection. Measurement of RTD, an intrinsic characteristic of the CRF rotary kiln incineration system, therefore is of importance. The instantaneous injection of a pulse of helium, followed by the sampling and analysis for helium concentration variations with time at downstream locations, is the experimental technique developed at the CRF to measure RTD.

For each experimental determination of RTD, a sharp pulse of helium was injected at one of the three ports shown schematically in Figure 27.

The technique is not straightforward, however, because of the necessity to conduct the sampled gas through some 12 meters of heat traced sampling lines and then through a gas conditioning system for measurement in a GC (all of which introduces its own RTD). What must actually be done is to first

TABLE 49. COMPARISON OF PREDICTED AFTERBURNER DESTRUCTION EFFICIENCIES

Rate Constant, k Sec^{-1}	Destruction Efficiency, DE Plug Flow Reactor $t_r = 1.5$ sec	 Composite Reactor $t_r = 1.5$ sec $b = 0.51$ sec
0.1	0.139	0.153
0.3	0.362	0.374
0.5	0.528	0.523
0.7	0.650	0.628
0.9	0.741	0.704
1.1	0.808	0.760
1.5	0.895	0.837
2.1	0.9571	0.9017
3.1	0.9904	0.9518
4.1	0.99787	0.9737
5.6	0.999524	0.9847
6.1	0.999894	0.99060
7.1	0.999976	0.99403
8.1	0.999995	0.99609

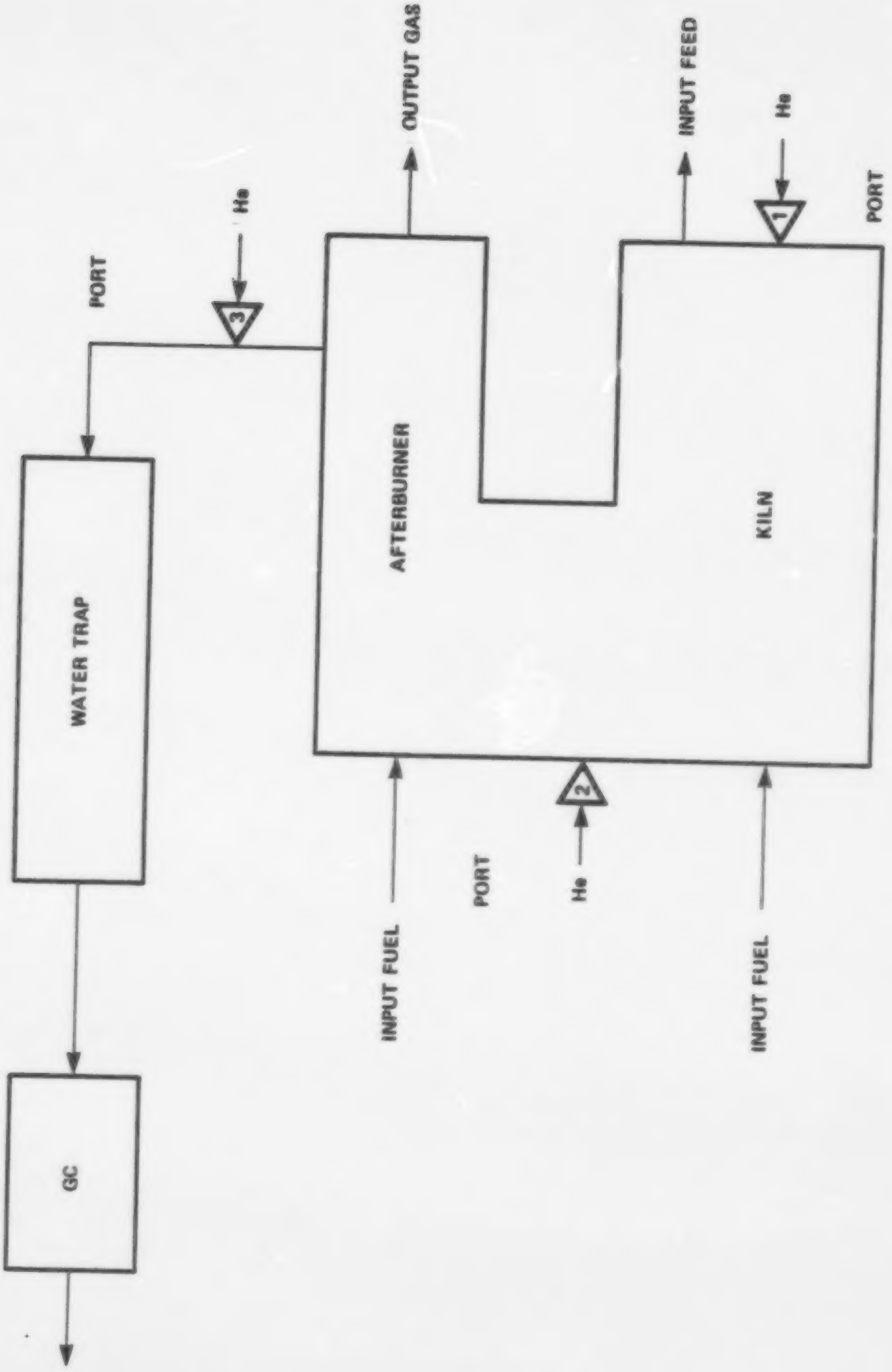
GC
WATER TRAP
PORT
3
He
AFTERBURNER
OUTPUT GAS
KILN
INPUT FEED
He
1
PORT
INPUT FUEL
PORT
2
He
INPUT FUEL

FIGURE 27. SCHEMATIC OF HELIUM INJECTION FOR RTD MEASUREMENTS

measure the RTD of the sampling-measurement system alone, and then measure that of the combined afterburner and measurement system. From these two measurements, the RTD of the afterburner is mathematically determined.

Initially, the RTD of the transfer line was to be determined by injecting a pulse of helium at port #3 and measuring the concentration, C, as a function of time with the gas chromatograph. Unfortunately, however, it takes about two minutes for all the gases to sweep over the GC-column - thus making it impossible to take continuous data and obtain the transient concentration from a single input-step. Consequently, a succession of input steps was employed - each yield a single data-point - and the system was allowed to sweep out all residual tracer (4 to 5 minutes required) from each input-step before the next was injected. Superposition of these results allowed the time-evolution of the helium concentration to be established. Measurement of the overall response curve for the afterburner/sampling system combination was carried out similarly, except that the helium pulses were injected at port #2.

As anticipated, the arrival of helium in the exit end of the chamber after the injection of a pulse at its entrance was not an abrupt increase in concentration but rather an event extended over a considerable period of time. Clearly, the chamber exhibits a distribution of residence times.

From the discussion in the preceding subsection, one model for the afterburner probability function is

$$f_{AB}(t) = \left[\frac{2}{t-b}\right]^2 (t-b) \exp - \left[\frac{2(t-b)}{t}\right].$$

A similar model was utilized for the separate probability function $f_k(t)$ for the kiln, and also for $f_s(t)$ for the sample transfer line. Using the property that for each of the three system elements

$$\frac{d(C_t/C_\infty)}{dt} = f(t),$$

measurement of C_t/C_∞, the ratio of helium concentration at time t to the steady-state helium concentration, enables the evaluation of f(t).

Figures 28, 29, 30 display typical experimental results. Injection of a helium pulse at the kiln feed face (Port 1 in Figure 27) provided data for Figure 28; injection at the kiln-to-afterburner transfer duct (Port 2 in Figure 27) provided data for Figures 29 and 30. Curves were fitted to the data in these figures.

Figures 31 and 32 show the individual f(t) probability functions, derived from the time-derivatives of Figures 28, 29, and 30, and via the mathematical extraction from combined-system data.

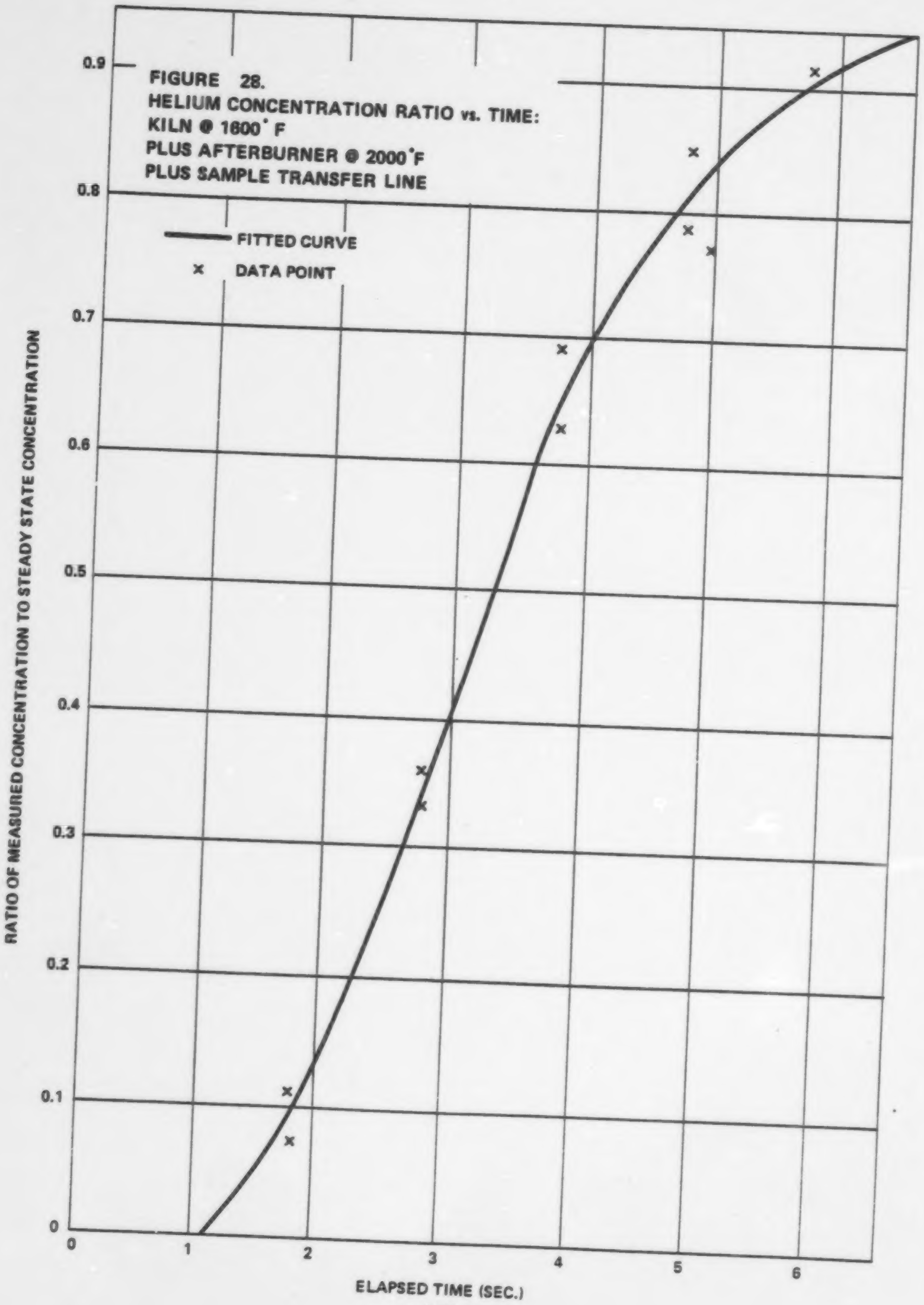

FIGURE 28.
HELIUM CONCENTRATION RATIO vs. TIME:
KILN @ 1600° F
PLUS AFTERBURNER @ 2000°F
PLUS SAMPLE TRANSFER LINE

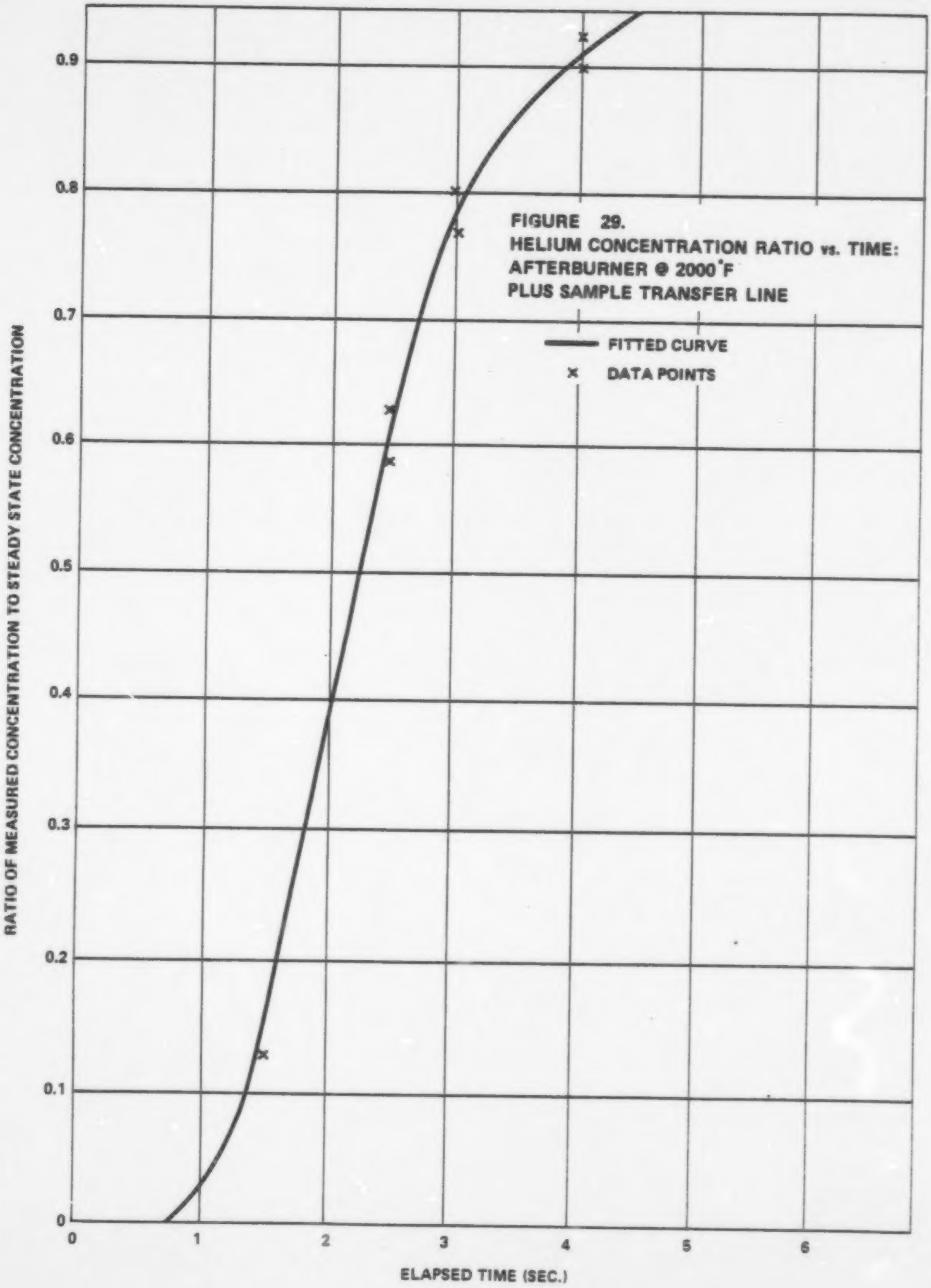

FIGURE 29.
HELIUM CONCENTRATION RATIO vs. TIME:
AFTERBURNER @ 2000°F
PLUS SAMPLE TRANSFER LINE

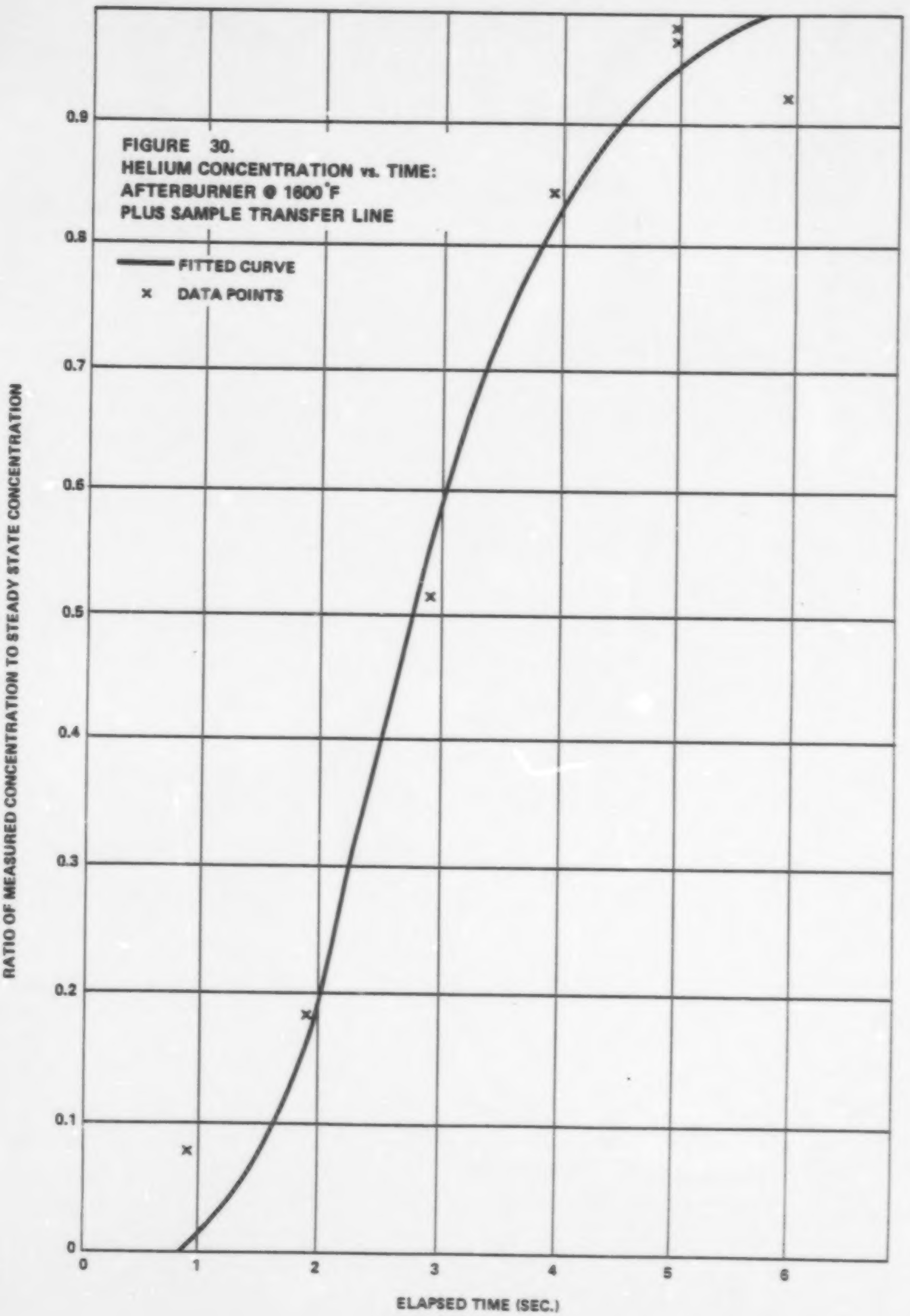

FIGURE 30.
HELIUM CONCENTRATION vs. TIME:
AFTERBURNER @ 1600°F
PLUS SAMPLE TRANSFER LINE

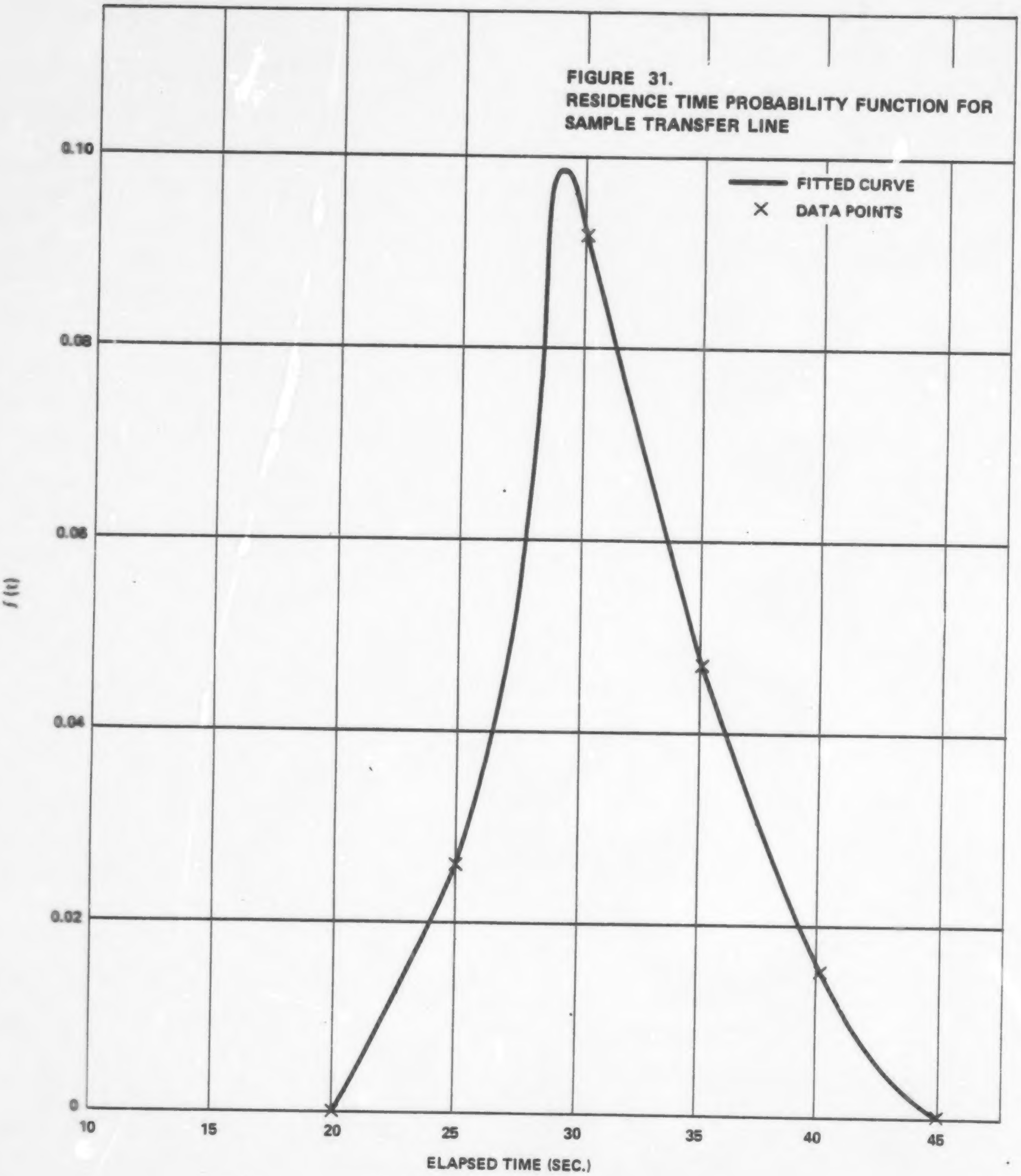

FIGURE 31.
RESIDENCE TIME PROBABILITY FUNCTION FOR SAMPLE TRANSFER LINE

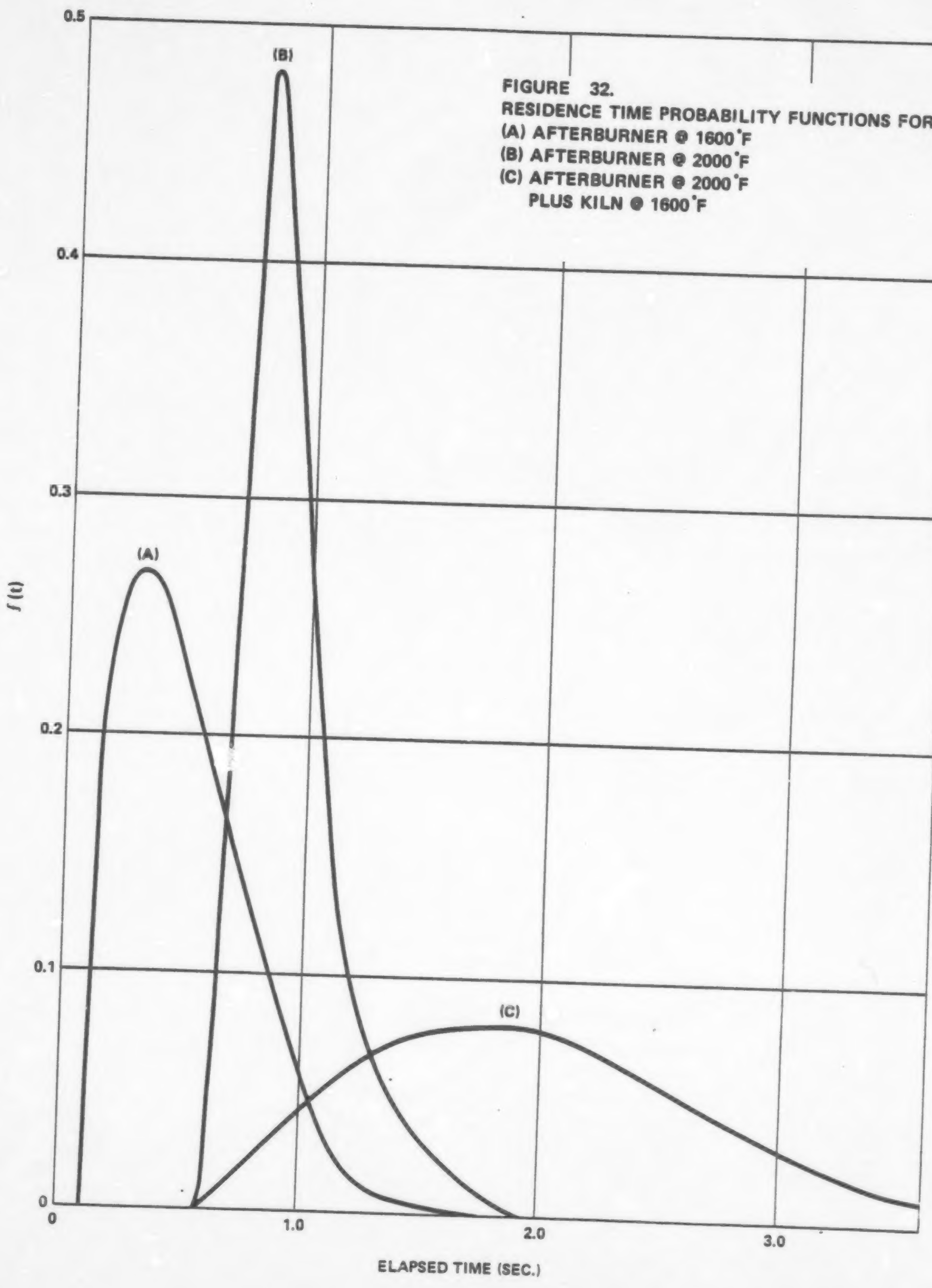

FIGURE 32.
RESIDENCE TIME PROBABILITY FUNCTIONS FOR
(A) AFTERBURNER @ 1600°F
(B) AFTERBURNER @ 2000°F
(C) AFTERBURNER @ 2000°F
PLUS KILN @ 1600°F

SECTION 6

SUPPORTING ANALYSES AND EXPERIMENTATION

FIXED PROBE VS TRAVERSE STACK SAMPLING

The experiments in the chlorinated benzene series conducted prior to 9/22/83 had all been conducted with stack sampling conducted by EPA Method 5 using a six point traverse on each of two perpendicular diameters. None of these experiments was found to have resulted in the collection of measurable particulates; in fact, the change in weight of the tared filter was essentially equal to the weight change associated with the pick up of atmospheric water when a dry filter was exposed to ambient air. Under these circumstances, the multipoint traverse sampling appeared to be unnecessary. In order to ensure that a traverse was not, in fact, required, an experiment was carried out on 22 September, 1983, in which simultaneous samples were taken in the stack, one using a traverse and the other a fixed probe. Both were conducted using hexachlorobenzene as the surrogate POHC and a standard Method Five Train.

Before presentation of the results, it is instructive to indicate the nature of the velocity distribution within the CRF stack. Figure 33 is such a profile derived during the experiment designed to test the need for stack traverse. Clearly, this distribution is somewhat unusual and the cause of such a distribution is not presently apparent.

Velocity pressure measurements were made with a standard S-type pitot at 9 sites on each traverse across the stack at both the high port and the low port (separated vertically by approximately 12 inches). This resulted in two perpendicular traverses. Simultaneously, each traverse point was accompanied by a helium dilution measurement. The average of the Δp was then computed according to the formula:

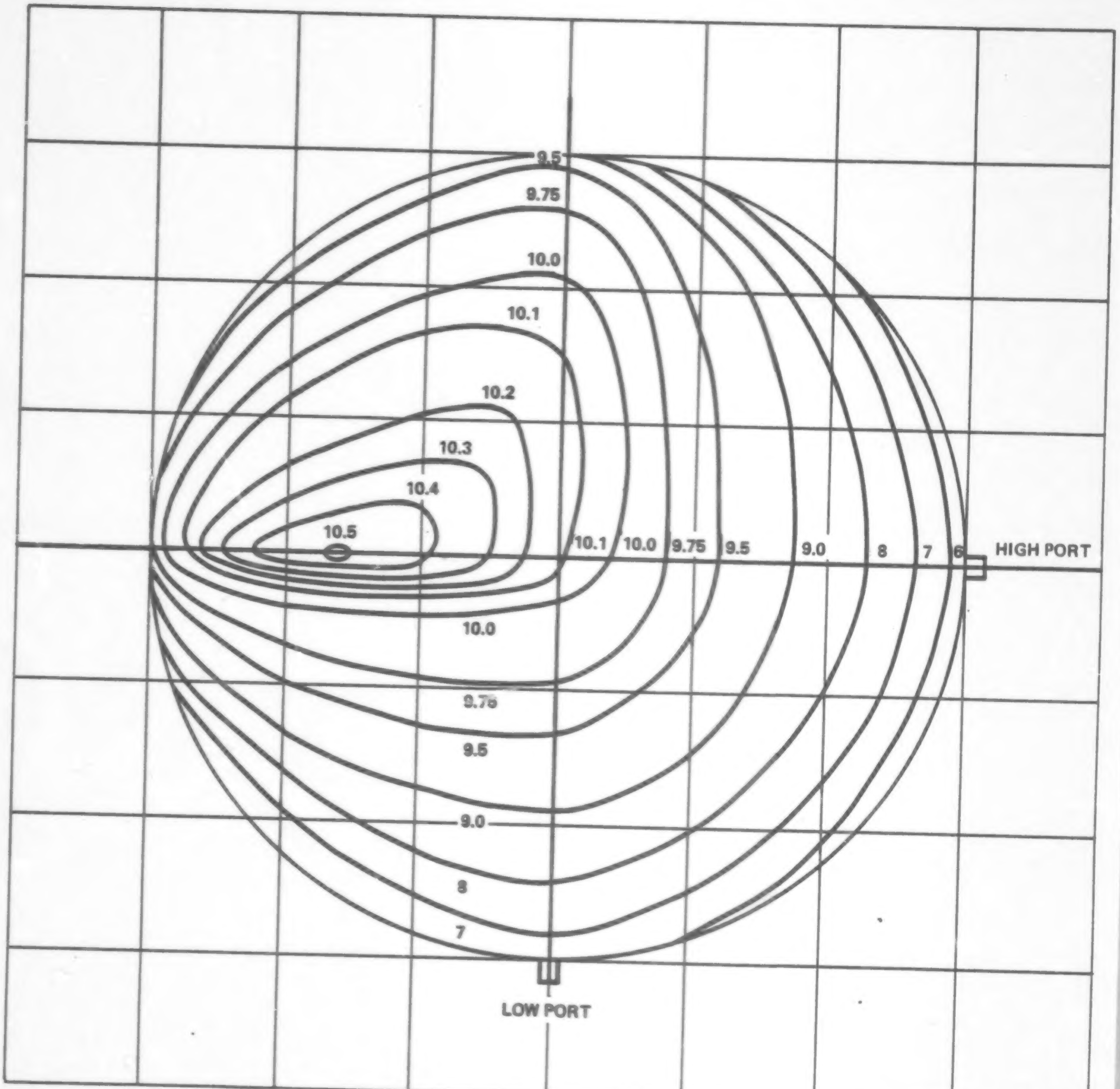

FIGURE 33. CRF STACK GAS VELOCITY MEASUREMENTS USING PITOT TUBE (VALUES SHOWN ARE VELOCITIES, FEET PER SECOND)

$$\overline{(\Delta p)^{1/2}} = \frac{\sum_{j=1}^{n} \left[(\Delta p_j)^{1/2} \right]}{n}.$$

Since the velocity at the point is proportional to $(\Delta p)^{1/2}$ and the average flow rate, $\bar{Q}$, is, in turn, proportional to $\overline{(\Delta p)^{1/2}}$, then

$$\bar{Q} = \alpha \, \overline{(\Delta p)^{1/2}}$$

where α is to be determined. On the other hand, since the He dilution measurements are a direct measurement of $\bar{Q}$, then the corresponding value of α may be determined by division as indicated by

$$\alpha = \frac{\bar{Q}}{\overline{(\Delta p)^{1/2}}}$$

Further, the average velocity is related to Q as follows:

$$\bar{V} \equiv \frac{\bar{Q}}{A}$$

where A is the cross-sectional area of the stack. Finally, one can relate the velocity (component parallel to the axis of the stack) at each point to the measured velocity pressure, $(\Delta p_j)^{1/2}$, by the relationship

$$V_j = \frac{\alpha}{A} (\Delta p_j)^{1/2}$$

The results of a typical traverse across the stack, as in Figure 33, show that the velocity distribution is skewed from the (approximate) parabola one would expect.

The data reported in Table 50 summarize the findings of the emission rates of several compounds as simultaneously measured with standard Method Five Train. The difference between the sample lies in the fact that one was accomplished isokinetically using a standard six position traverse while the other was sampled with a fixed position probe. Examination of the results reported in Table 50 shows that the results for low boiling compounds (toward

TABLE 50. A COMPARISON OF FIXED PROBE vs TRAVERSE IN STACK

ANALYTE*	Sample S09221138-1 Traverse Probe Q_{out} (μg/min)	Sample S09221138-2 Stationary Probe Q_{out} (μg/min)
C15-EANE	5.13	5.45
1,3-DCBZ(m)	104.99	52.2
C16-EANE	31.7	20.3
1,4-DCBZ(p)	—	30.8
BENZYL Cl	69.6	37.9
HC-1,3-BD	0.947	0.510
1,2,4-TCBZ	21.3	13.1
1,2,4,5-TCBZ	6.0	—
C15-BZ**	87.6%	82.5%
1,2-DCNAPHTH	195	—
C16-BZ	22.7	0.904
GAMMA-BHC	1.3	0.5

*Nomenclature Spelled Out In Table 38

**% Recovery of Pentachlorobenzene Spike the top of the table) are somewhat different from those with boiling points (lower on the table). The measured emission rates of the latter are significantly higher for the isokinetic traverse as compared to the fixed probe.

The immediate reaction to these observations would be to assert that there is a significant particle load in the stack and that the higher the boiling point, the more likely that the compound would be associated with the particulate at the stack temperature of 81°C. Certainly one would anticipate that the isokinetic traverse would see a more representative sample of stack particulates and thereby see higher emission rates of the high boilers. Actual measurements of the particulate loading have been frustrated since the loading is so small that the changes in filter weight caused by its pickup of atmospheric humidity are larger. On the other hand, as reported in Table 39, every sample for which analysis of the phthalate content was conducted showed significant concentrations of this class of compounds. Perhaps, at 81°C, phthalates and other high-boiling organic can form small aggregates (particles) which, when captured on a heated filter (as in the Method 5), could be expected to volatilize to eventually appear in the train. If this were the case, it would explain the observation of a very low particulate loading as an artifact of the nature of the particulates and also would explain the results in Table 50. Further investigation is required before the differences between fixed probe and traverse sampling can be understood.

HOT ZONE SAMPLING

General Considerations

When sampling a gas stream which is expected to contain particulates, special precautions must be taken if the particulate sample is to be representative of the particulate distribution within this gas stream. Specifically, the sampling probe orifice must be pointed upstream (into the flow) and the flow velocity through the orifice must be exactly the flow that would pass through that space in the absence of the sampling orifice. Clearly, in order to accomplish this the flow must be laminar having velocity components only in the direction of flow. Normally, such a situation is ensured by the selection of the sampling point in a long straight section of ducting at a point at least 8 diameters downstream and not less than 3 diameters upstream of any constriction or change in direction of the mass flow. At the CRF such conditions occur approximately in the stack but nowhere else in the system.

On the other hand, the two zones of the CRF incinerator that are of importance for hot zone sampling, the kiln and afterburner exhaust ducts, meet none of the above conditions. In addition to being located at points that do not meet the physical requirements, the flow in these zones is deliberately non-laminar in order to induce mixing and, hopefully, concentration uniformity of all chemical species. Clearly, in these zones there is little hope of obtaining a representative sample of particulates and virtually no hope of ever determining the degree to which a given sample deviates from the actual distribution. It would thereby appear that there is little utility in hot zone sampling. Actually, the very fact that the gas phase temperatures are always well above the normal boiling point of any of the molecular species of interest strongly suggests that such species will be in the gaseous state and thus would appear as isolated molecules. If this be indeed the case, then sampling for particulates is only of academic interest except within the stack (this for reasons of compliance with RCRA regulations).

A second point relative to sampling for particulates in laminar flow must be made. Because the flow is laminar and because the thin annular zone of the flow immediately adjacent to the walls of the duct is essentially at rest, the velocity profile across the duct is not uniform. That is to say, the velocity of that portion of the flow surrounding the axis of the duct is the highest. This usually shows up as a parabolic velocity distribution in laminar flow in a duct of circular cross-section. Now, the forces that cause a particle to move with the mass flow are frictional forces which are proportional to the relative velocity of the particle as compared to the gases. If one considers a particle of sufficient size, then these frictional forces on the two sides of the particle are different (because of the velocity gradient). This condition produces several results: (1) the particle will experience a torque and will therefore rotate, and (2) there will normally be a component of force normal to the axis of the duct on the center of gravity of the particle that will tend to cause it to move toward the zone of highest velocity and smallest velocity gradient, i.e., the center of the duct. This latter phenomenon will normally result in size segregation of the particles. For this reason, it is standard practice to sample such a duct by making a traverse, that is to say, to sample the duct at a number of positions in a plane normal to the flow direction. At each point, the pumping speed through the sampler is adjusted as indicated above. The combination of traversing the plane normal to the flow with carefully compensated sample pumping rate is the process known as "isokinetic sampling".

As has been described above, the sampling probes in the hot zones of the CRF incinerator are simple 0.953 cm (0.375 in) stainless tubes fixed in position as was indicated in Figure 16. Clearly there is no attempt at a traverse nor at a match of the localized velocities. The justification for this approach is based on the assertion that the molecular species of concern are present as free molecules (or at worst, in small molecular associations) and thereby are distributed by Brownian diffusional forces rather than by macroscopic forces as in the discussion of the dynamics of macroscopic particles. If this is correct, then a traverse would yield no more information than the fixed probe.

The results of the fixed probe versus traverse experiment (9/22/83) shown on Table 50 indicate that, in the stack where laminar flow predominates, the traverse produced much larger amounts of higher-boiling organics than the fixed probe, but this does not apply directly to the hot zones where the flow is more turbulent.

Kiln Transfer Duct Sampling Equipment

As has been discussed above, the basic premise underlying the use of a fixed probe in hot zone sampling is the assertion that, because of the high ambient temperature, organic molecules in either the kiln transfer duct or the afterburner outlet duct would not be associated with particles but would exist in the gaseous state. In a series of experiments wherein the kiln transfer duct was sampled using a fixed sampling probe, a short stainless sampling line, and an in-line glass fiber filter with a Modified Method Five Train, the kiln conditions were selected so as to produce soot during a feed of 1,2,4-TCB

TABLE 51. SUMMARY OF ANALYTE DISTRIBUTION IN KILN SAMPLES

	Sample No. K01131109						Sample No. K01131211					
	Line Wash		Filter		Resin		Line Wash		Filter		Resin	
Analyte*	(µg)	%	(µg)	%	(µg)	%	(µg)	%	(µg)	%	(µg)	%
1,3-DCBZ(m)	0.072	5.5	0.064	4.9	1.18	90	—	—	0.188	28	0.494	72
1,4-DCBZ(p)	—	—	0.193	100	—	—	—	—	0.340	59	0.233	41
CL6-EANE	—	—	—	—	—	—	—	—	—	—	0.0313	100
1,2-DCBZ(o)	—	—	0.0369	5.1	0.690	95	—	—	0.100	29	0.243	71
BENZYL-CL	—	—	0.0536	4.0	1.30	96	—	—	0.109	56	0.0865	44
1,3,5-TCBZ	0.007	2.7	0.029	11	0.221	86	0.009	8.0	0.0458	39	0.0616	53
1,2,4-TCBZ	11.6	10	19.7	17	82.9	73	10.3	19	24.8	46	18.6	35
CL5-BZ	—	—	0.009	100	—	—	—	—	—	—	—	—
CL6-BZ	0.018	40	0.022	49	0.005	11	0.0019	3.8	0.044	87	0.0048	9.5
DEP	0.176	12	0.912	63	0.369	25	0.264	5.4	4.40	91	0.187	3.8
DNBP	—	—	3.96	69	1.76	31	—	—	34.3	100	—	—
BUBZP	—	—	1.57	100	—	—	0.617	20	2.11	69	0.326	11
BZEHP	—	—	—	—	—	—	—	—	18.4	100	—	—
TOTAL PHTHLATES	0.176	2	6.44	74	2.13	24	0.881	1	59.2	98	0.513	1
SAMPLING TIME	20 min.						6 min.					
FILTER TEMP.	31°C						32°C					
SOOT WEIGHT	133.9 mg						120.8 mg					
FEED	Propane/Toluene/1,2,4-TCB						Propane/Toluene/1,2,4-TCB					
KILN TEMP.	548°C						540°C					

*Nomenclature from Table 38.

TABLE 51. SUMMARY OF ANALYTE DISTRIBUTION IN KILN SAMPLES (Con't)

	Sample No. K10241225						Sample No. K01241350					
	Line Wash		Filter		Resin		Line Wash		Filter		Resin	
Analyte	(µg).	%	(µg)	%	(µg)	%	(µg)	%	(µg)	%	(µg)	%
1,3-DCBZ(m)				--	--	—	0.0048	1.7	0.274	98.5	—	—
1,4-DCBZ(p)	--	--	--	--	--	—	0.271	58.2	0.195	41.8	--	—
1,2-DCBZ(o)	--	--	--	--	--	--	—	—	0.191	12.6	1.33	87.4
BENZYL-CL	--	--	--	--	--	--	0.394	19.2	0.133	6.5	1.53	74.4
1,3,5-TCBZ	0.0013	5.7	0.0014	6.2	0.020	88.1	0.0075	1.1	0.194	28.6	0.477	70.3
1,2,4-TCBZ	0.056	0.5	1.02	9.5	9.61	89.9	6.98	2.1	124	37.0	204	60.7
CL5-BZ	0.001	2.4	0.0099	40.9	0.0137	56.7	0.005	9.6	0.0296	54.50	0195	35.9
CL6-BZ	0.001	5.4	0.0054	27.3	0.0132	67.3	0.003	12.5	0.0139	53.8	0.0087	33.7
DEP 38.4		0.033	1.9	0.622	36.1	1.07	62.0	0.531	36.1	0.375	25.5	0.565
DNBP —		--	—	1.83	52.7	1.64	47.3	1.88	23.5	6.13	76.5	—
BUBZP	0.011	4.0	0.047	17.2	0.216	78.8	1.52	88.2	,0.124	7.2	0.079	4.6
TOTAL PHTHLATES	0.044	1.0	2.50	46	2.93	53	3.93	35	6.63	59	0.644	6
SAMPLING TIME	49 min.						53 min.					
FILTER TEMP.	97.8°C						93.3°C					
SOOT WEIGHT	2.0 mg						18.5 mg					
FEED	Propane/Toluene						Propane/Toluene/TCB					
KILN TEMP.	510°C						588°C					

TABLE 51. SUMMARY OF ANALYTE DISTRIBUTION IN KILN SAMPLES (Con't)

	Sample No. K01131252						Sample No. K01241050					
	Line Wash		Filter		Resin		Line Wash		Filter		Resin	
Analyte	(µg)	%	(µg)	%	(µg)	%	(µg)	%	(µg)	%	(µg)	%
1,3-DCBZ(m)	—	—	0.297	37	0.514	63	—	—	—	—	—	—
1,4-DCBZ	--	—	0.240	100	--	—	—	—	—	—	—	—
1,2-DCBZ	—	—	0.176	40	0.268	60	--	--	—	—	0.071	100
BENZYL-CL	—	—	0.047	100	--	—	0.482	100	--	--	--	—
1,3,5-TCBZ	0.018	15	0.058	49	0.044	37	—	—	—	—	0.016	100
1,2,4-TCBZ	13.8	20	22.7	48	10.5	22	0.290	2.0	0.228	1.7	13.1	96.2
CL5-BZ	—	--	0.005	100	--	--	--	--	--	—	0.003	100
CL6-BZ	—	—	0.009	68	0.0043	32	0.005	24.5	0.005	24.5	0.0104	50.9
DEP	0.479	36	0.843	64	-	—	0.85	36.2	0.689	29.4	0.806	34.4
DNBP	—	—	3.01	100	--	—	—	—	7.99	100	—	--
BUBZP	0.539	26	1.53	74	—	—	2.05	67.2	0.242	7.9	0.760	24.9
BZEHP	—	—	2.55	100	--	—	3.95	100	--	--	--	—
TOTAL PHTHLATES	1.02	11	7.93	89	—	—	6.95	40	8.92	52	1.57	8
SAMPLING TIME	13 min.						39 min.					
FILTER TEMP.	31.7°C						56.1°C					
SOOT WEIGHT	52.8 mg						9.1 mg					
FEED	Propane/Toluene/TCB						Propane					
KILN TEMP.	566°C						488°C					

in toluene. The results of these experiments are summarized in Table 51. For the moment consider only the TCB collected and the total soot collected. There apparently is no correlation between amount of soot collected and the amounts of analytes collected on the filter. This indicates that within high temperature zones the association of organic molecules with the soot particles may not be important. It then follows that the basic assumption for hot zone sampling that the organics are in the vapor state is, in fact, valid.

Several other features of the data in Table 51 should be touched on. There appears to be no obvious mechanism operating that determines in which of the three media (line, filter or resin) a specific chemical species will be found or how it is partitioned between the three media. Clearly, the total sample must include all three media. As has frequently been observed in the past, the longer the sampling time the more likely that the volatile species will not remain on the filter but will be collected on the resin.

It is also useful to note that the two experiments K01241050 and K01241225, which followed experiment K01131252 wherein TCB was fed, show that residues of the higher boiling chlorinated benzenes remained in the kiln to show up in later experiments. This phenomenon has been observed in both high temperature chambers as well as in the scrubber system.

Replicate Hot Zone Sampling

Acquisition of replicate samples is important to sampling QC, and several attempts to obtain replicates of hot zone samples were made as described below. Careful consideration resulted in adopting the approach of sampling the kiln transfer line with three simultaneous samplers. (This rather than a time sharing approach.) It was planned that there would be a common probe (1/4 inch stainless steel) terminating in a stainless steel tubing cross from which each of the individual samplers was fed. Each sampler was fitted with its own vacuum pump, rotameter and (calibrated) gas meter. The sampling (common) line, also 1/4" stainless steel, was of sufficient length to cool the gas sample to a temperature in the range of 250°F. This is required since the XAD-2 temperature must be as low as possible, and the available refrigerated water supply is sufficient to cool the effluent gas from the sampler to less than 50°F provided the inlet gas temperature is no higher than 250°F. The geometry and dimensions of the sampling system are shown in Figure 34.

In order to present the samplers with a realistic situation, the following experimental conditions were maintained during the test:

Kiln Temperature: 1400°F
A.B. Temperature: 1800°F
Feed Rate : 100gm/hr TCB;2.8 l/hr in C_7H_8
Sampling Point : Kiln Transfer Duct
Probe : 30 l/min
Samplers : 10 l/min
Sampling Time : ~90 min

Several points should be made:

- Under these conditions in the kiln, considerable production of soot is observed.
- The sampling probe is in a fixed position with the orifice pointing downstream.
- Evidence to date suggests that PICs are formed primarily when the temperature is sufficiently low as to allow soot formation.

Each sampler was adjusted so that its sampling rate was 10 l/min. At the completion of the experiment, the total collected sample volumes were as listed below:

Sampler	Collected Volume (std. liters)
1	823
2	817
3	805

The sample volume data above indicate that the maximum difference in collected volumes was of the order of 2%. Thus, one would expect a difference in the residual concentrations of the collected chemical species to be of this order of magnitude.

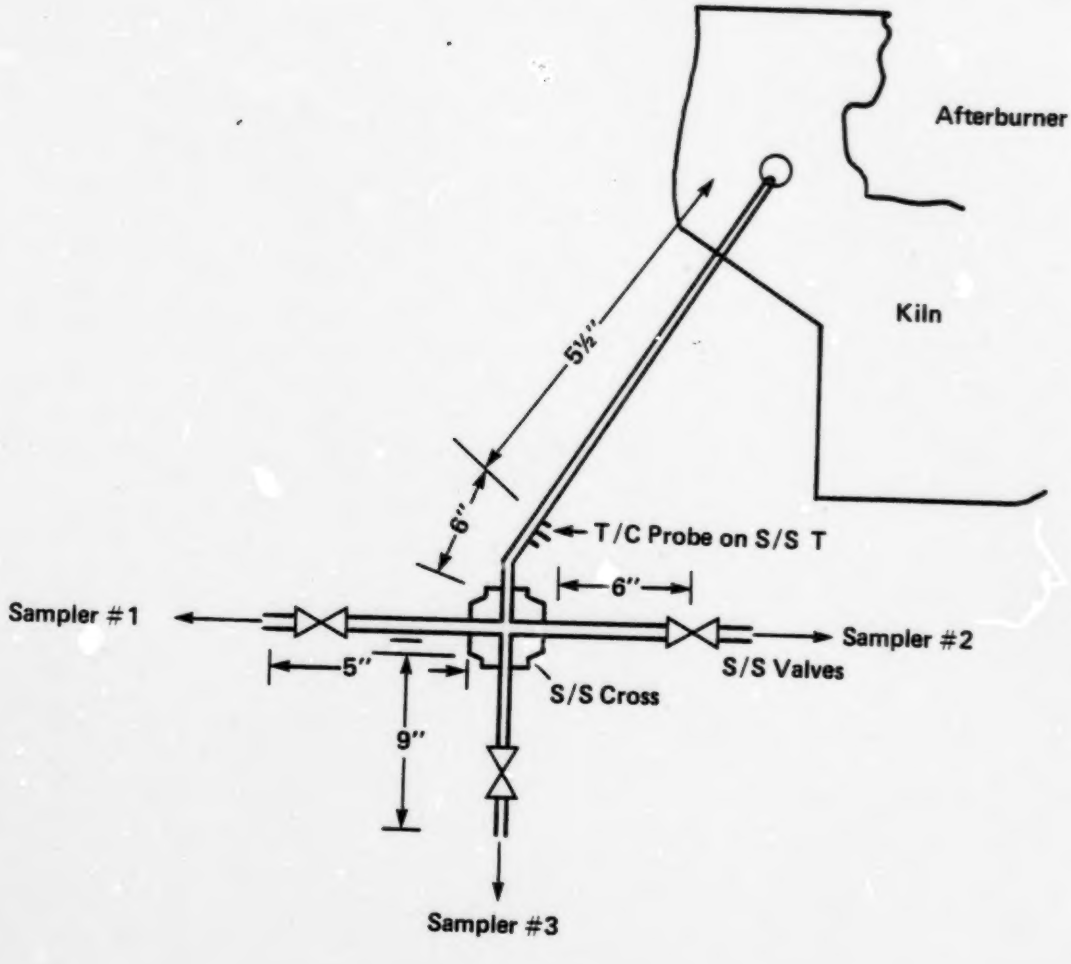
Afterburner
Kiln
5½"
6"
T/C Probe on S/S T
6"
Sampler #1
Sampler #2
S/S Valves
5"
S/S Cross
9"
Sampler #3

FIGURE 34. GEOMETRY OF REPLICATE SAMPLING SYSTEM

Visual Observations - Soot Buildup

At the end of the sampling period it was observed that the frit and, to a lesser extent, the resin in all three samplers were stained with soot. The original basis for the placement of the probe in a fixed position with the orifice facing downstream was the premise that the gas flow conditions existing within the kiln transfer duct (as well as the afterburner outlet duct) were such that isokinetic sampling was not possible. Under these circumstances, and considering the high temperatures existing in the transfer duct (which should cause all volatile species to be in the gaseous state: i.e., not associated with particles) the proper arrangement of the probe orifice would be such as to avoid particles as much as possible. The observed collection of soot in the sampler apparently indicates that the relatively high pumping speed (13 l/min) at the probe orifice caused sufficient flow disturbance as to "suck" in soot particles.

Experimental Results

At the completion of the sampling period (90 minutes) the three samplers and the sampling manifold were removed to the analytical laboratory. Each of the Battelle samplers and their XAD-2 resin beds were treated as separate analytical samples. The resin was washed into a Soxhlet thimble and the sampler back-flushed with methylene chloride into the Soxhlet. A total of 250 ml of solvent was used in the flush which subsequently became the extractant for the resin. The entire sampling line and manifold was flushed with acetone/methylene chloride and formed a fourth separate sample. After sample concentration, analysis was accomplished with GC using ECD detection.

The experimental results are depicted in Table 52.

Discussion of Results

It is immediately obvious that the main purpose of this experiment was not met since in no sense were the three samples "replicates". Before launching into a detailed discussion it is necessary to report several qualitative findings.

- Each of the three samplers was darkened especially in the sintered disk. The darkening is presumed to have been the results of soot collected.

TABLE 52. EXPERIMENTAL RESULTS* FOR SIMULTANEOUS KILN TRANSFER SAMPLES

Sample	Pentachlorobenzene** C_6HCl_5 (μg)	Hexachlorobenzene** C_6Cl_6 (μg)	Trichlorobenzene $C_6H_3Cl_3$ (μg)
#1	0.214	0.91	0.051
#2	0.013	0.067	0.0097
#3	0.029	0.20	0.016
linewash (soot)	0.005	0.98	0.84

* The listed amounts of each chemical represent the total collected in each sample.

** These two compounds are tentatively identified PICs from incineraion of trichlorobenzene.

- The line washing resulted in a strongly colored solution again apparently arising from soot collected on the sample line.
- The gas temperature (as measured at the upstream end of the cross, as shown in Figure 34) was found to be 121°C (250°F) and the diameter of the sampling line was 0.635 cm (1/4"). With each of the samplers pumping at the rate of 13 l/min, the gas velocity as the sample entered the cross (at the rate of 39 l/min) was of the order of 2150 cm/sec.
- Clearly, the analytical results from the line wash suggest that the PICs that were found were associated with soot. Either the soot association existed within the kiln or occurred after the soot condensed on the sampling line wall. This point, which is critical for the method of hot zone sampling, will be addressed in more detail below.
- Referring to Figure 34, it would be supposed that the ballistics of the cross would result in larger amounts of material being collected in sampler #3. The analytical results clearly indicate that this expectation was not fulfilled.
- Uncertainties have been introduced by the procedures used to remove the sample from the Battelle samplers; specifically, after the resin was removed to the Soxhlet thimble, the sampler was back flushed with the solvent which was then introduced into the Soxhlet extractor. In this manner there is no distinguishing between that portion of the recovered organics taken up in the resin and that associated with the soot.
- Since neither C_6Cl_6 nor C_6HCl_5 was introduced in the feed; then at a kiln temperature of 760°C (1400°F) the products of incomplete combustion from the POHC, $C_6H_3Cl_3$, include these two compounds. These compounds were not observed in samples collected at a kiln temperature of 871°C.

Alternatives For QA/QC On Hot Zone Sampling

In spite of the obvious failure to meet the goal of the above experiment, which was to replicate hot-zone samples and thus determine the degree to which quantitative hot-zone sampling and analyses can be relied upon, the very real finding of two readily identified PICs must be considered to fully justify the effort. Nevertheless, some form of replicate measurement is still considered mandatory in order to validate hot-zone data.

Analysis of the experimental data suggests that an attempt to sample with several samplers simultaneously is probably not going to yield useful results. Further, the fact is that the sample stream geometry shown in Figure 34 results in each stream having a different geometry. It is apparently necessary that the sample path be exactly the same for each sampler. This can only be accomplished by either of two approaches, neither of which will produce replicates taken simultaneously. With the first method, operation of the several samplers on a time sharing basis with each operated in turn for 5 minutes with the cycle repeated until each sampler has collected a total of approximately 1.0 SCM. The cycling can be accomplished using a four position sampling (GC) valve which is designed to provide a geometrically identical path for the gas sample irrespective of which position has been selected. The second method of obtaining non-simultaneous duplicate samples requires that the several samples be taken using the identical sample path with the complete sample taken. On completion of the first sample period, the sampler removed and then the second sampler placed in position, the sample taken and so on; i. e., consecutive samples.

Several additional features of the two methods, in addition to serving the prime function of providing replicate determinations, should be pointed out. It is highly probable that there are spontaneous fluctuations of short temporal duration in the concentration of the POHC of interest. Thus, in the sharing mode, contiguous samples (5 minutes duration) may very well show considerable variations in effective concentrations. However, when these variations are averaged over some 20 successive sampling intervals, these spontaneous fluctuations should be averaged out. Under these circumstances, the procedure should yield comparable results and thus provide legitimate replicate samples.

The second method produces samples even further removed from true simultaneous replicates. On the other hand, there is another facet of incinerator operation that can be tested by this approach. Under conditions of constant feed rate, constant chamber temperatures, constant excess air and so forth, it would be of significant value to measure fluctuations in the residual concentration of POHC. In the event that the first method yields acceptable and comparable equivalent gas phase concentrations but the second method does not, the results obtained will add to our knowledge of the efficacy of control methods based on operator accessible parameters.

Consecutive QA/QC Samples

A five way chromatographic valve was obtained and found to be heavily contaminated as a result of the machining. The contamination resisted all effort at removal short of complete disassembly. Finally, the device was disassembled and successfully cleaned but could not be sealed on re-assembly. The manufacturer then informed us that the system could only be sealed using a suitable lubricant which, of course made the five-way valve useless for the purpose of time-sharing replicate measurements.

As the only alternate available then, the consecutive sampling method was adopted. A portion of these data are reported in Table 53 for samples K01131109, K01131212 and K01131252.

The important point to note here is that every effort was made to keep the conditions of the system constant during the overall sampling period. That is to say, the feed rate, kiln temperature, POHC (TCBZ), and excess air in the kiln were all kept as constant as possible. Several points immediately attract attention:

a. Essentially the same species are present in all samples

b. In several species, the emission rate is essentially the same in the first two samples. In these same species the first and third samples show considerable differences

TABLE 53. KILN TRANSFER SEQUENTIAL SAMPLES (selected from Table 39)

ANALYTE*	K0113 1109 (µg/min)	K0113 1211 (µg/min)	K0113 1252 (µg/min)
CL5-EANE	0.461	<0.055	<0.055
1,3-DCBZ(m)	123	129	67.5
1,4-DCBZ(p)	18	108	20.0
1,2-DCBZ(o)	67.7	64.4	36.9
BENZYL-CL	126	36.9	3.92
1,3,5-TCBZ	23.9	22.0	10.0
1,2,4-TCBZ	10,600	10,100	3,910
CL5-BZ	0.839	<0.037	0.393
CL6-BZ	4.28	9.51	1.11
DEP	136	909	110
DNBP	535	6450	250
DUBZP	147	573	172

*Symbols identified in Table 38.

c. The DE_K for the POHC is essentially the same for the first and second samples but quite different from the third sample

d. With respect to the phthalates, the first and third samples differ widely from the second sample.

Except for the phthalates, the results for the first two samples appear, from Table 53, to be very similar, but the third sample appears not to repeat the first two. From Table 36, both the CO_2 and CO levels were dropping throughout the test, and there appeared to be a significant drop in CO level between the second and third samples. The lack of reproducibility may have resulted from normal temporal variations in kiln conditions throughout a test. More study of such variations and their effects on PIC and POHC emissions is needed. From the work on replicate sampling to date, it appears that system variations, under relatively constant feed rates and kiln temperature, are sufficient to cause significant variations in kiln emissions.

SCRUBBER POHC MASS TRANSPORT ANALYSIS

The APC system can be, in certain cases, responsible for a part of the DRE, via:

$$DRE = DE + RE - (DE)(RE)$$

Where DE is the incinerator destruction efficiency and RE is the removal efficiency of the APC system. In attempting a material balance across the APC system, it becomes necessary to determine both the input and the output of the APC system. The former will, in general, be determined by hot zone sampling for both POHC concentration by extractive sampling and for mass flow by He dilution measurement. The output consists of that portion of the POHC carried off by the flue gases in addition to that portion removed via the blowdown. The flue gas contribution is determined by stack measurements while the blowdown contribution is determined by sampling the blowdown water.

In this context, it becomes of concern to determine when the blowdown should be sampled. The following model attempts to address this question.

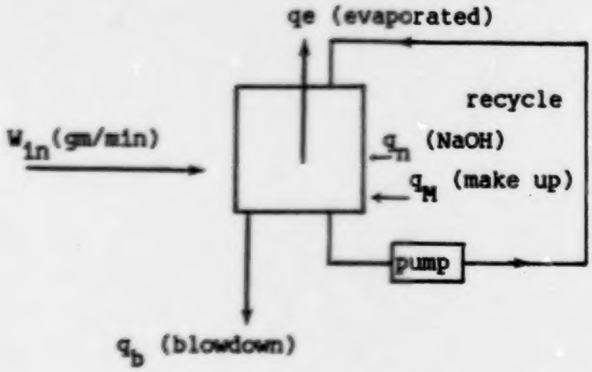

FIGURE 35. MODEL OF CRF SCRUBBER

Let the total water mass be Q(gm), then

$$Q = q_m + q_n - q_e - q_b = 0 \quad \text{(where the q's are rates in gm/min)} \qquad (1)$$

$$q_m + q_n = q_e + q_b \qquad (2)$$

If there is no volatilization of the POHC at the scrubber temperature then the rate of change of the POHC concentration, c(t), is given by:

$$\frac{dc(t)}{dt} = \frac{W_{in}}{Q} - c(t)\,\frac{q_b}{Q} \qquad (3)$$

Which may be rewritten in the form:

$$\frac{dc(t)}{dt} + c(t)\,\frac{q_b}{Q} = \frac{W_{in}}{Q} \qquad (4)$$

Now, if each term is multiplied by $\exp\left(\frac{q_b t}{Q}\right)$, the result may be rewritten as

$$\frac{d}{dt}\left[c(t)\exp\left(\frac{q_n t}{Q}\right)\right] = \frac{W_{in}}{Q}\exp\left(\frac{q_b t}{Q}\right) \qquad (5)$$

Which now allows separation of variables to yield

$$\int_{c(o)}^{c(t)}\left[d\ \ c(t)\exp\left(\frac{q_b t}{Q}\right)\right] = \frac{W_{in}}{Q}\int_{t_o}^{t}\exp\left(\frac{q_b t}{Q}\right)dt \qquad (6)$$

Which, W_{in} assumed to be constant, on integration and insertion of limits where $t_o = 0$, $c(o) = 0$, becomes

$$c(t)\ \exp\left(\frac{q_b t}{Q}\right) = \frac{W_{in}}{q_b}\ \exp\left[\left(\frac{q_b t}{Q}\right) - 1\right] \tag{7}$$

$$c(t) = \frac{W_{in}}{q_b}\left[1 - \exp\left(-\frac{q_b}{Q}\right)t\right] \tag{8}$$

Which, for very long times, becomes

$$c(t \to \infty) \sim \left(\frac{W_{in}}{qb}\right) \tag{9}$$

Thus, many C(t) measurements should be made late in the experiment. The resulting plot of C(t) vs t (after feed incineration) should asymptotically approach a constant value with a time constant of Q/q_b (from Equation 9).

The same argument can be used in the event that the POHC is not soluble in the scrubber liquor and has significant vapor pressure at the scrubber temperature. The model must be extended by considering the losses to the stack (as measured by stack sampling). This case is not pertinent to the POHCs considered herein but will be verified using the EPA Soup mixture.

CHLORIDE ION IN THE SCRUBBER BLOWDOWN

As summarized in Equation (8) above, the concentration of a non-volatile, water soluble species in the scrubber blowdown should increase with time with a time constant equal to the ratio of total water mass flow rate, Q, to the blowdown water removal rate, q_b. Since Q=120 gal and q_b=2 gal/min, the time constant should be 60 minutes. Further, the concentration should reach (asymptotically) a value of W_{in}/q_b which, in the case of this specific experiment for which W_{in}=261.5 gm/hr, is roughly 565 ppm (by weight) assuming that all the organic chlorine has been converted to the inorganic form of HCl. Figure 36 is a plot of the theoretical approach to steady state on which are superimposed a number of measured values taken at different times after the initiation of organic chlorine feed. The measurements were taken with a freshly calibrated Orion chloride specific probe.

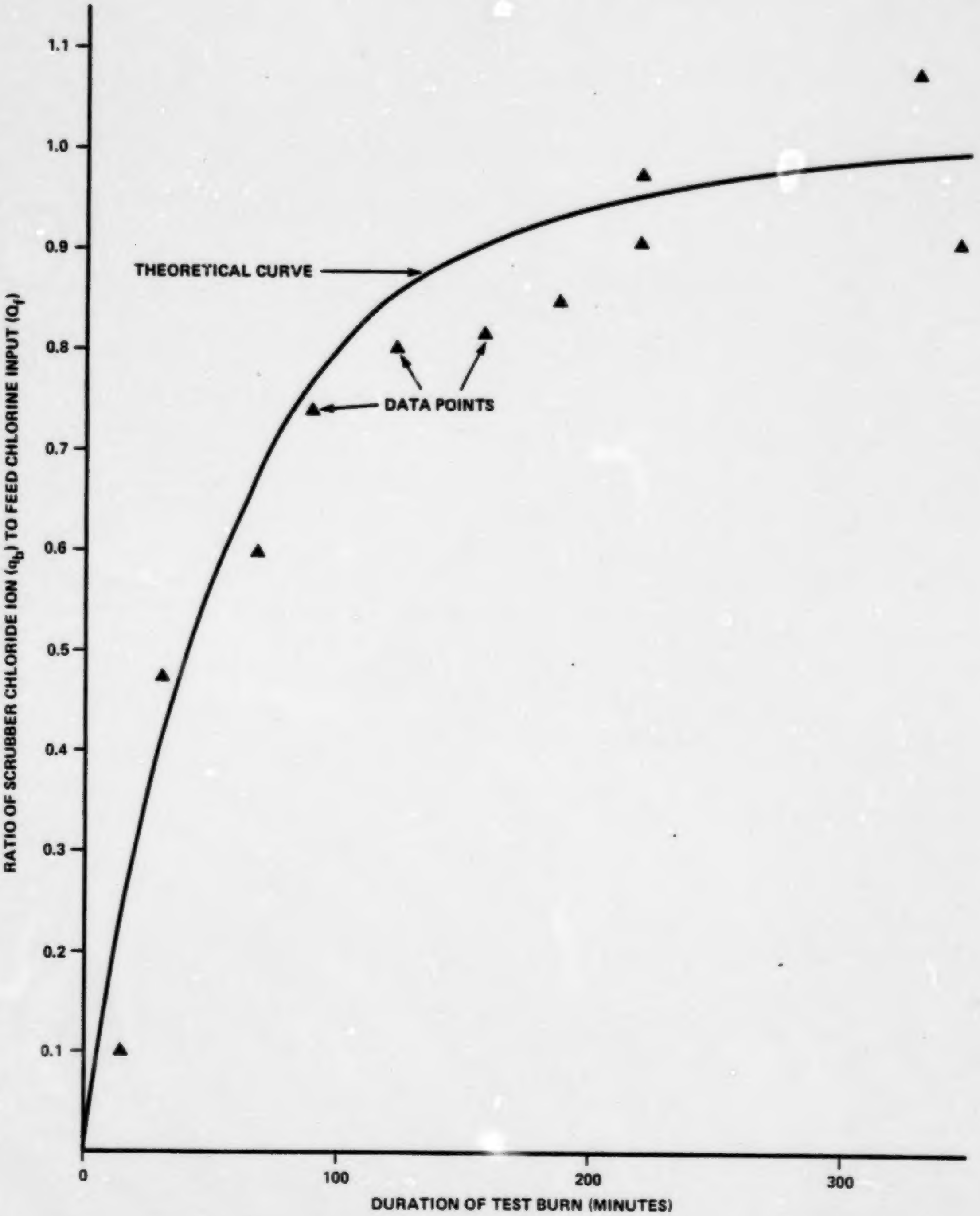

FIGURE 36. PLOT OF THE RATIO OF SCRUBBER CHLORIDE ION OUTPUT (q_b) TO FEED CHLORINE INPUT (Q_f) AS A FUNCTION OF TIME DURING A TEST BURN (Q_f = 4.36 gm/min)

Examination of Figure 36 shows excellent agreement with the model except for the rather significant spread in data at times approaching the steady state values. The origin of this variability will be investigated in future experiments.

SECTION 7

QUALITY ASSURANCE AND QUALITY CONTROL

CRF QUALITY ASSURANCE PROGRAM PLAN

The discussion in Section 6 on attempts to obtain replicate hot zone samples is a good example of the innovative quality control tests needed for the CRF Program. The requirement for quality control, and general guidelines for data quality, are established by the CRF QA Program Plan, which was developed and implemented by the CRF staff.

It is the expressed goal of the Environmental Protection Agency that all data generated within the Agency, either intramurally or extramurally via contracts, be of highest quality. To assure that this is indeed the case, EPA requires that all EPA regional offices, program offices, and EPA laboratories participate in a centrally managed quality assurance (QA) program. This requirement applies to all environmental monitoring and measurement efforts mandated or supported by EPA through regulations, grants, contracts, or other formalized means not currently covered by regulations. Each office or laboratory, for example the Combustion Research Facility, has the responsibility to implement minimum procedures which assure that precision, accuracy, completeness, and representativeness of its data are known and adequately documented. As a part of this program each organization must set criteria for the acceptability of data.

To ensure that all data generated within the agency is uniformly acceptable, EPA requires that all program units prepare a Quality Assurance Program Plan (specified in QAMS-004/80) and a QA Project Plan (QAMS-005/80). The laboratories at IERL-EPA-Cincinnati have implemented a program plan for all member laboratories. The Combustion Research

Facility has prepared a formal QA/QC Project Plan which specifies its approach to maintaining data quality. This document has been reviewed by EPA and is now fully implemented.

The QA/QC project plan, as developed by the CRF, must be considered a working document because so many of the details (particularly performance criteria) are unknown or untried in their application to incineration. In addition a specific real-world waste or an EPA Soup may require waste-specific procedures. These details can only be included in the QA/QC project plan as they are derived.

QA/QC activities relevant to facility/system operation and maintenance and QC procedures for engineering measurements have been described previously in Sections 1 and 2, respectively. Sampling and analytical QA/QC activities are presented below.

The Health and Safety Program in place at the Combustion Research Facility also is administered by the CRF staff under general guidelines set out in the QA Program Plan. Safety considerations plan an important role in determining experimental protocols and operational procedures. A summary description of the CRF Health and Safety Program is included in this section.

QA/QC CONSIDERATIONS FOR CRF SAMPLING AND ANALYSIS

In current parlance, quality assurance refers to the plan by which data of known quality may be generated, while quality control specifies those activities which must be carried out in order to generate and verify such data. These two areas are reported in detail in the CRF QA Program Plan. The following discussion will cover the narrower field of analytical chemical quality control as it supports the data reported. Special emphasis will be made in the areas of blanks, surrogates, control charts and performance evaluation studies. Precautions and procedures with respect to safe handling of standard reference materials, formulation and recordation of standard solutions, calibration of the gas chromatograph and so forth are essentially those of Sherma in "Manual of Analytical Quality Control for Pesticides and Related Compounds in Human and Environmental Samples - Second Revision", NTIS #PB81-222721. Analytical and preparative methods are those found in "Test Methods for Evaluating Solid Waste - Physical/Chemical Methods", USEPA, SW-841, second edition.

Blanks

Each incinerator sample type for a given burn day is accompanied by a blank sample which is analyzed in parallel with it. Analysis of this blank sample measures the contribution of interferants by solvents, reagents, glassware, sampling media and preparative/analytical methods. Each analytical chemical result in this report has been corrected for these interferants.

Use of Surrogates and Control Charts

For present purposes, a surrogate is a compound added in known quantity to an incinerator sampling train prior to its use in sampling. Pentachlorobenzene (1.38µg) was added to impinger #2 of the Method 5 (M5) trains, while octafluorobiphenyl (20.0µg) was added to the XAD-2 sampling medium of the Modified Method 5 (MM5) trains. After a specimen of flue gas has been taken using such a spiked train, analysis will reveal not only the compounds present in the flue gas but also the recovery of the added spike. For economy of space in presentation, these recovery data are displayed as control charts (Sherma, vide infra) in Figure (37) and Figure (38). Comparison of these figures dramatically demonstrates the superior performance of the MM5 trains in that their data are roughly centered on zero SEU, and an excursion beyond two SEU (roughly comparable to the familiar two-sigma limits) is rare. In contrast, the M5 data are severely distorted in the direction of low recoveries.

Thus, the use of surrogates and control charts has been shown to be a useful technique for rapidly and unambiguously flagging an analytical process as in or out of control. Although not presented here, control charts have been routinely maintained at the CRF for more than twenty compounds for which analyses are often done, in several matrices.

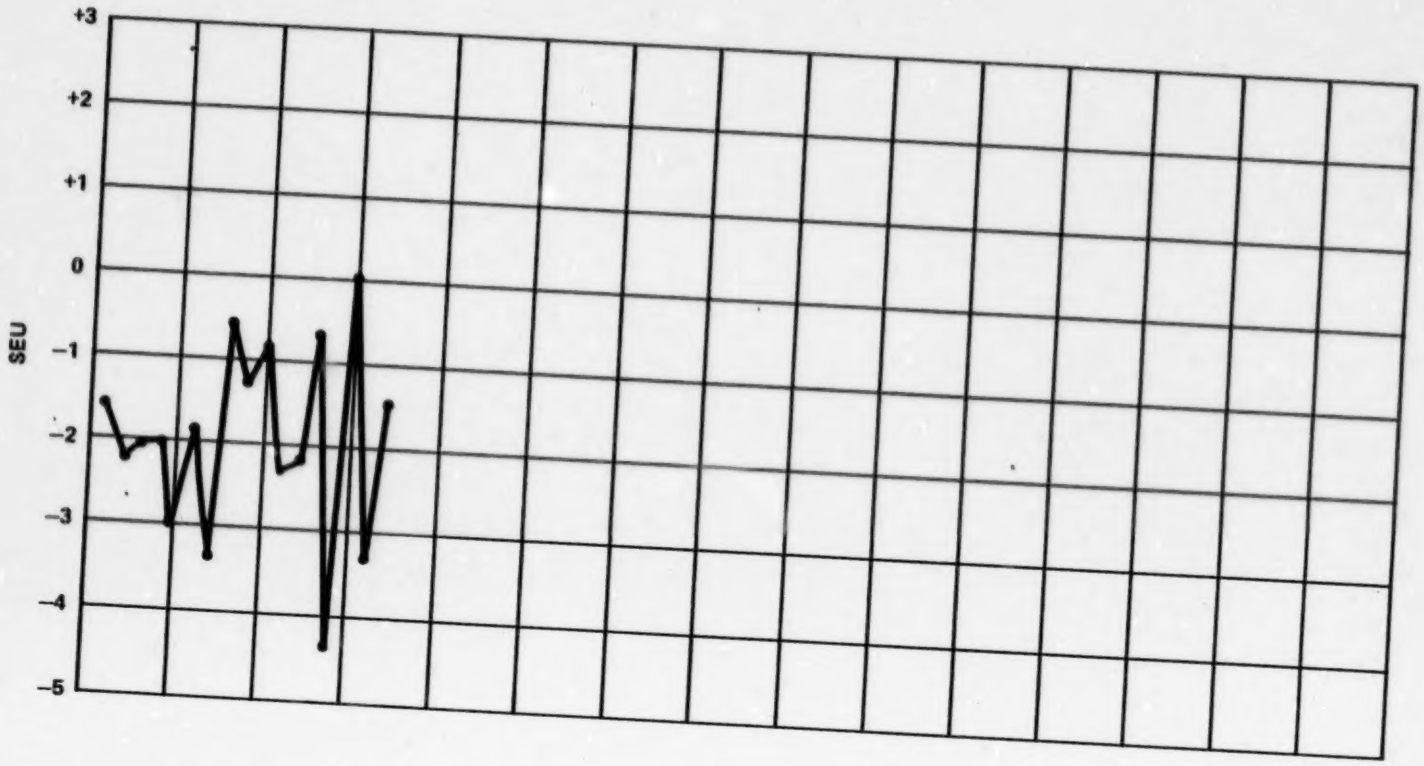

FIGURE 37. CONTROL CHART FOR PENTACHLOROBENZENE SURROGATE IN METHOD 5 STACK SAMPLING TRAINS.

Spike level = 1.38 micrograms.
1 SEU = 0.112 micrograms.
Mean recovery, x = 1.159 micrograms.

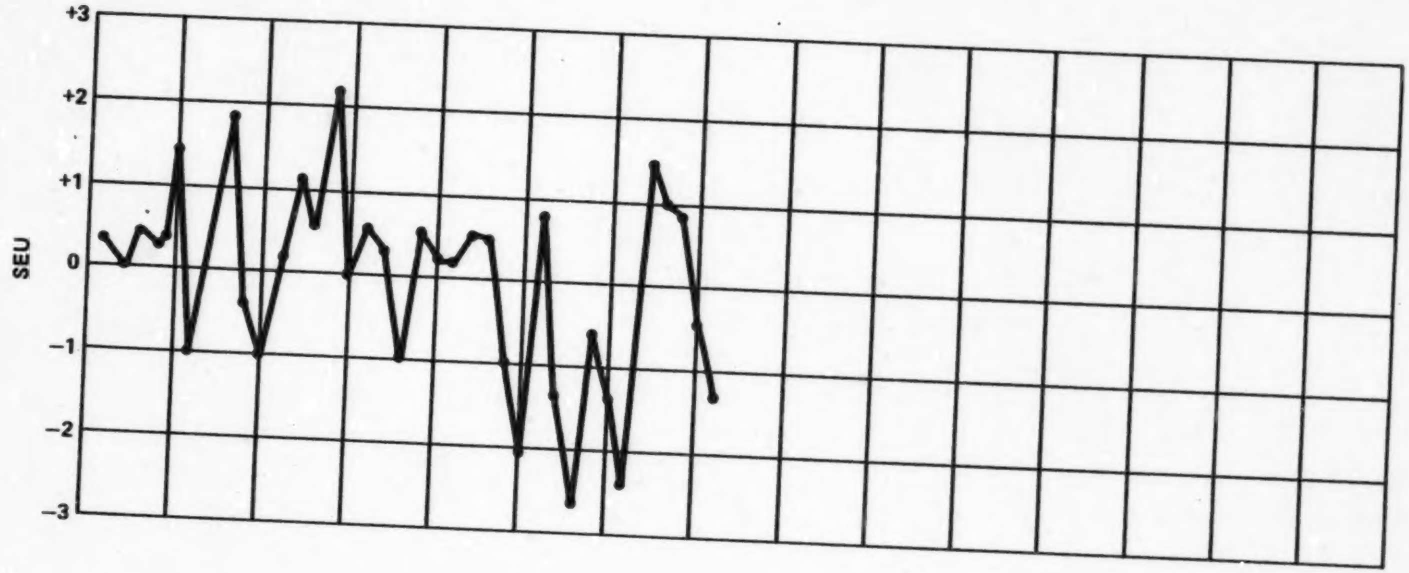

FIGURE 38. CONTROL CHART FOR OCTAFLUOROBIPHENYL SURROGATE IN MODIFIED METHOD 5 HOT ZONE SAMPLING TRAINS.

Octafluorobiphenyl Spike level = 20.0 micrograms.
1 SEU = 2.04 micrograms.

Intramural Performance Evaluation

Periodically, the competence of the analysts and the proper functioning of an analytical method is demonstrated and documented through the device informally known as "qualifying rounds". Briefly, a sample matrix is chosen and spiked with known amounts of a variety of pure compounds. Staff analysts are required to each analyze five aliquots of this preparation and compare their results to the nominally known true values. Table 54 displays the results of such an exercise for a water matrix. It should be emphasized that this device can only demonstrate the precision of staff and method.

Extramural Performance Evaluation

In order to assess the accuracy of staff and method, another device commonly known as "PAT Rounds" is employed. The Quality Assurance Officer, USEPA, IERL-Ci, makes available to participating laboratories spiking solutions, the composition of which is not known to the recipient. A water matrix is inoculated with these solutions, analyzed and the results are reported to EPA which subsequently issues a Performance Evaluation Report. Such a report is shown in Table 55 for methods in use at the CRF. The single poor result on Table 55 stems from an arithmetic error.

The data contained in Tables 54 and 55 show that the analytical procedures (including methods, operators, and instruments) in use at the CRF are in control, with very good precision and accuracy. Should any question arise concerning an experimental data point, the raw data and data reduction procedures are documented and available, along with appropriate calibration data and other QA/QC information.

Comparison of Sampling Methodologies

As a portion of the on-going QA/QC program there are several portions of the sampling program that have undergone significant testing, particularly the spike and recovery tests on the standard Method Five Train (M5) and on the Modified Method Five Train (MM5). In planning the implementation of the QA program it was deemed that, because it is saturated with water vapor at 81°C (178°F), the stack gas stream would most severely tax the sampling train. To simulate the stack stream, the spiked train was used to sample stream from a

TABLE 54. INTRAMURAL PERFORMANCE EVALUATION STUDIES

PARAMETER	SPIKE LEVEL (µg/1)	REPLICATE # AND % RECOVERY				
		#1	#2*	#3	#4	#5
PENTACHLOROETHANE	0.656	96.3	65.1	90.4	96.1	91.2
1,3-DICHLOROBENZENE	9.21	96.3	65.8	91.0	96.4	93.5
1,4-DICHLOROBENZENE	20.2	97.0	66.2	91.6	97.0	94.1
HEXACHLOROETHANE	5.12	98.0	66.8	93.0	98.2	95.9
1,2-DICHLOROBENZENE	7.80	98.2	66.9	91.9	98.5	95.2
BENZYL CHLORIDE	8.00	100.4	64.4	92.5	100.9	95.4
1,3,5-TRICHLOROBENZENE	3.44	102.0	68.9	95.6	102.0	100.0
HEXACHLORO-1,3-BUTADIENE	0.800	106.7	71.3	99.8	106.9	104.2
1,2,4-TRICHLOROBENZENE	4.99	106.0	71.3	99.2	106.4	103.2
HEXACHLOROCYCLOPENTADIENE	8.03	107.3	70.2	102.0	108.8	105.9
1,2,4,5-TETRACHLOROBENZENE	0.853	105.4	70.9	100.2	106.0	102.2
1,2,3,4-TETRACHLOROBENZENE	0.490	102.7	69.3	91.4	103.6	99.2
2-CHLORONAPHTHALENE	22.2	102.2	69.3	97.9	102.5	99.9
PENTACHLOROBENZENE	0.437	101.6	68.9	96.9	101.7	99.6
1,2-DICHLORONAPHTHALENE	4.00	100.0	69.8	96.2	100.5	100.0
HEXACHLOROBENZENE	1.02	100.0	69.5	97.5	101.0	100.0
ALPHA-BHC	2.00	101.5	69.0	96.0	102.5	100.0
GAMMA-BHC	3.66	101.6	68.6	95.9	102.2	99.5
1,2,3,4-TETRACHLORONAPHTHALENE	4.00	100.5	69.0	99.0	101.2	97.5

* Replicate #2 "bumped" severely once during the evaporative concentration step of its preparation. These data are not included in any calculations, but are displayed here to illustrate one type of problem which may occur in trace organic analysis.

TABLE 54 (Continued)

PARAMETER	SPIKE LEVEL (µg/l)	REPLICATE # AND % RECOVERY				
		#6	#7	#8	#9	#10
PENTACHLOROETHANE	0.656	81.0	91.5	94.8	96.1	89.3
1,3-DICHLOROBENZENE	9.21	84.8	93.9	96.1	97.8	92.9
1,4-DICHLOROBENZENE	20.2	84.4	94.4	96.3	98.7	93.6
HEXACHLOROETHANE	5.12	81.6	93.4	96.0	98.6	92.5
1,2-DICHLOROBENZENE	7.80	83.9	94.7	97.7	100.1	94.4
BENZYL CHLORIDE	8.00	89.7	97.4	104.8	107.0	97.0
1,3,5-TRICHLOROBENZENE	3.44	89.2	99.5	102.4	104.4	98.9
HEXACHLORO-1,3-BUTADIENE	0.800	88.6	99.9	103.1	104.8	98.2
1,2,4-TRICHLOROBENZENE	4.99	89.8	99.2	102.7	104.6	93.8
HEXACHLOROCYCLOPENTADIENE	8.03	100.5	108.3	109.8	112.0	111.8
1,2,4,5-TETRACHLOROBENZENE	0.853	89.8	99.2	103.2	104.0	99.5
1,2,3,4-TETRACHLOROBENZENE	0.490	92.5	98.6	103.3	105.4	99.4
2-CHLORONAPHTHALENE	22.2	93.4	100.8	103.2	104.2	100.0
PENTACHLOROBENZENE	0.437	90.5	97.5	102.4	103.6	97.6
1,2-DICHLORONAPHTHALENE	4.00	92.5	98.6	102.7	103.6	98.5
HEXACHLOROBENZENE	1.02	91.6	97.5	101.3	102.0	97.5
ALPHA-BHC	2.00	90.8	96.7	100.7	102.1	96.8
GAMMA-BHC	3.66	90.8	95.9	101.0	101.9	96.1
1,2,3,4-TETRACHLORONAPHTHALENE	4.00	90.8	95.9	101.0	101.5	96.1

TABLE 54 (Continued)

PARAMETER	SPIKE LEVEL (µg/l)	REPLICATE # AND % RECOVERY					AVERAGE % RECOVERY	R.S.D. %
		#11	#12	#13	#14	#15		
PENTACHLOROETHANE	0.656	95.7	90.4	95.6	93.7	96.2	92.7	4.6
1,3-DICHLOROBENZENE	9.21	91.5	91.6	95.9	94.0	96.5	93.7	3.6
1,4-DICHLOROBENZENE	20.2	97.0	92.5	96.5	94.5	97.0	94.6	3.8
HEXACHLOROETHANE	5.12	97.3	93.2	96.9	95.7	97.8	94.9	4.6
1,2-DICHLOROBENZENE	7.80	97.1	92.4	96.3	94.1	97.0	95.1	4.2
BENZYL CHLORIDE	8.00	98.8	93.0	97.6	95.4	98.4	97.7	4.7
1,3,5-TRICHLOROBENZENE	3.44	100.0	95.1	98.8	97.3	99.7	98.9	3.8
HEXACHLORO-1,3-BUTADIENE	0.800	100.9	95.9	99.9	98.5	101.0	100.6	4.7
1,2,4-TRICHLOROBENZENE	4.99	100.9	96.4	100.0	98.8	101.4	100.2	4.6
HEXACHLOROCYCLOPENTADIENE	8.03	102.3	99.0	103.0	102.1	104.4	105.5	4.0
1,2,4,5-TETRACHLOROBENZENE	0.853	102.4	98.3	98.1	100.7	103.3	100.9	4.0
1,2,3,4-TETRACHLOROBENZENE	0.490	100.8	96.4	100.4	99.0	101.6	99.6	4.1
2-CHLORONAPHTHALENE	22.2	103.0	98.2	101.7	102.2	103.9	100.9	2.9
PENTACHLOROBENZENE	0.437	100.9	95.6	100.4	100.0	102.2	99.3	3.5
1,2-DICHLORONAPHTHALENE	4.00	101.0	96.0	100.5	100.5	102.2	99.5	3.0
HEXACHLOROBENZENE	1.02	100.9	95.0	99.6	100.0	101.6	99.0	2.9
ALPHA-BHC	2.00	101.0	94.0	99.7	100.2	101.7	98.8	3.4
GAMMA-BHC	3.66	100.0	93.0	99.5	99.5	101.0	98.4	3.6
1,2,3,4-TETRACHLORONAPHTHALENE	4.00	99.5	93.0	99.4	99.8	100.6	98.3	3.3

TABLE 55. PERFORMANCE EVALUATION REPORT WATER POLLUTION STUDY NUMBER WP011

LABORATORY: AR001 VERSAR

DATE: 12/14/83

PARAMETERS	SAMPLE NUMBER	REPORT VALUE	TRUE VALUE*	ACCEPTANCE LIMITS	WARNING LIMITS	PERFORMANCE EVALUATION
PCB'S IN MICROGRAMS PER LITER:						
PCB-AROCLOR 1242	1	0.818	0.840	.341- 1.13	.444- 1.03	ACCEPTABLE
PCB-AROCLOR 1254	1	8.15	9.17	3.64- 11.9	4.69- 10.8	ACCEPTABLE
PCB-AROCLOR 1260	1	3.38	3.32	2.05- 4.30	2.34- 4.01	ACCEPTABLE
PESTICIDES IN MICROGRAMS PER LITER:						
ALDRIN	1	0.804	0.910	.243- 1.15	.357- 1.03	ACCEPTABLE
	2	0.152	0.182	.0568- .222	.0778- .201	ACCEPTABLE
DIELDRIN	1	0.458	0.423	.254- .601	.299- .557	ACCEPTABLE
	2	0.179	0.242	.0952- .354	.128- .321	ACCEPTABLE
DDD	1	0.474	0.555	.307- .777	.367- .717	ACCEPTABLE
	2	0.730	0.093	.0407- .151	.0546- .137	NOT ACCEPTABLE
DDE	1	0.221	0.221	.150- .349	.175- .323	ACCEPTABLE
	2	0.740	0.735	.327- 1.00	.413- .915	ACCEPTABLE
DDT	1	0.859	0.837	.335- 1.21	.447- 1.10	ACCEPTABLE
	2	0.216	0.167	.0455- .261	.0727- .233	ACCEPTABLE
HEPTACHLOR	1	0.704	0.753	.354- .939	.428- .865	ACCEPTABLE
	2	0.144	0.151	.0556- .207	.0749- .188	ACCEPTABLE
HEPTACHLOR EPOXIDE	1	1.17	1.18	.592- 1.62	.723- 1.49	ACCEPTABLE
	2	0.230	0.235	.0621- .357	.0997- .320	ACCEPTABLE
CHLORDANE	5	0.488	0.620	.232- .952	.322- .861	ACCEPTABLE
	6	3.66	4.64	1.78- 6.67	2.40- 6.05	ACCEPTABLE

*BASED UPON THEORETICAL CALCULATIONS, OR A REFERENCE VALUE WHEN NECESSARY.

boiling flask of water; i.e., simulated steam distillation. For the M5 train, the analytes were spiked into the second impinger in isooctane. Upon passage of the steam through the train, the spiked analyte was collected in isooctane in the third impinger, and the contents of both impingers were subsequently extracted and analyzed. The results for the M5 train are displayed in Tables 56 and 57.

For the MM5 train, using XAD-2 resin in the Battelle sampling module, the analytes were spiked into the resin and the exit stream from the module passed through an impinger containing isooctane. The results for three samples are shown in Table 58. Background corrections were available and were applied to the two samples collected on 30 November. It is obvious from Tables 56 and 58 that the MM5 recoveries were much more reproducible and more complete than those with the M5 train.

The relatively low recoveries seen in Table 56 suggested that the liquid impinger train would not be satisfactory for hot zone sampling. The low recoveries were attributed to the excessive loss of the isooctane impinger fluid resulting from the inability to sufficiently cool the gas stream prior to admission to the impinger. On the other hand, the fact that the sample gas must first pass through the condenser of the Battelle sampler prior to exposure to the XAD-2 resin should make the MM5 sample more acceptable for hot zone sampling.

HEALTH AND SAFETY PROGRAM

Perhaps the most publicly sensitive issue associated with the handling and disposal of industrial wastes results from the fact that many such wastes are potentially hazardous to human health and/or to the environment. Thus, the issue of the safety with which these materials are handled and finally disposed of is of great importance.

In recognition of this importance, safety has been made an integral part of all operations at the CRF including not only work practices and personal protection, but also in the design of equipment. To translate the concern for safety at the CRF into reality, a formal Safety Program has been organized and implemented by the contractor in consultation with USEPA Health and Safety Personnel.

TABLE 56. AVERAGE SPIKE AND RECOVERY FOR M5 TRAIN FROM REPETITIVE STEAM DISTILLATION TESTS+

ANALYTE*	Spike Level (μg)	Average Recovery (μg)	Average (%)	RSD (%)
CL5-EANE	0.0657	0.0323	48.2	35.12
1,3-DCBZ(m)	0.9207	0.702	76.2	20.43
1,4-DCBZ(p)	2.020	1.495	74.0	19.0
CL6-EANE	0.5116	0.380	74.3	17.7
1,2-DCBZ(o)	0.7804	0.598	76.6	16.5
BENZYL CL	0.8000	0.584	73.0	24.26
1,3,5-TCBZ	0.344	0.307	89.3	13.11
HC-1,3-BD	0.080	0.0681	85.2	22.5
1,2,4-TCBZ	0.499	0.455	91.4	10.86
HCCPD**	0.8026	0.469	58.4	87.59
1,2,4,5-TCBZ	0.0853	0.0794	93.04	10.48
1,2,3,4-TCBZ	0.0490	0.0456	92.98	13.92
2-CL-NAPHTH	2.222	2.125	95.6	11.36
CL5-BZ	0.0437	0.0457	104.6	12.1
1,2-DCNAPHTH	0.4000	0.3882	97.05	37.63
CL6-BZ	0.1015	0.0881	86.8	16.8
ALPHA-BHC	0.2004	0.176	87.9	14.5
GAMMA-BHC	0.3661	0.3397	92.8	14.5
1,2,3,4-TCNAPHT	0.4000	0.3866	96.6	12.96

* Identity of symbols in Table 38.

** Photosensitive, leading to great variation between samples.

+ Average over many repetitions. For a more typical case involving the loss of most of the isooctane, see Table 57.

Note: RSD = Relative Standard Deviation

TABLE 57. SPIKE RECOVERY DATA FOR VARIOUS ANALYTES COLLECTED IN AN ISOOCTANE IMPINGER VIA STEAM DISTILLATION FROM ISOOCTANE

ANALYTE*	SPIKE** (μg)	M08091400-I_2 (%R)	M08091400-I_3 (%R)	Total Recovery $\sum$%R
CL5-EANE	0.7086	0.7	52.7	53.4
1,3-DCBE(m)	9.730	-0-	60.03	60.3
1,4-DCBZ(p)	21.38	-0-	61.1	61.1
CL6-EANE	5.50	-0-	65.8	65.8
1,2-DCBZ(o)	8.20	1.0	78.9	79.9
BENZYL-CL	8.33	1.0	47.4	48.4
1,3,5-TCBZ	3.66	0.8	72.7	73.5
HC-1,3-BD	0.855	2.0	74.1	76.1
1,2,4-TCBZ	5.27	4.2	76.7	80.9
1,2,4,5-TCBZ	0.963	31.8	91.0	122.9
1,2,3,4-TCBZ	0.515	58.7	78.5	137.2
2Cl-NAPHTH	23.69	20.0	81.7	101.7
CL5-BZ	0.4695	32.3	86.6	118.9
1,2-DCNAPHTH	4.000	36.2	66.1	102.3
CL6-BZ	1.09	84.7	42.4	127.1
ALPHA-BHC	2.16	54.6	21.6	76.2
GAMMA-BHC	3.94	60.7	14.0	74.7
1,2,3,4-TCNAPHTH	4.31	84.9	8.8	93.7

* Symbols defined in Table 38

** Spike added to isooctane in second impinger. Analyses conducted of content of second and third impinger of the train. The initial volume of isooctane in I_2 was 250 ml. After samples were taken, the final volume in I_2 was 94 ml H_2O. In addition the final contents of I_3 were 140 ml isooctane and 30 ml H_2O whereas it was initially empty.

TABLE 58. RECOVERY FROM BATTELLE SAMPLER CONTAINING 22g XAD-2 RESIN (MM5 TRAIN)

Analyte*	SK Level µg Added	M11071505		M11301014		M11301015		Average
		SK µg Found	%R	SK µg Found Bk Corr	%R	SK µg Found Bk Corr	%R	%R
CL5-EANE	0.06557	0.6561	100	0.06702	102	0.06844	104	103
1,3-DCBZ(m)	0.9207	0.921	100	0.841	91.3	0.861	93.5	92.4
1,4-DCBZ(p)	2.0196	2.017	99.9	1.906	94.4	1.962	97.1	95.8
CL6-EANE	0.51156	0.512	100	0.4537	88.7	0.4647	90.8	89.8
1,2-DCBZ(O)	0.7804	0.780	99.9	0.717	91.9	0.717	91.9	91.9
BENZYL CL	0.8000	0.796	99.5	0.744	93.0	0.728	91.0	92.0
1,3,5-TCBZ	0.3440	0.342	99.4	0.337	98.0	0.345	100	99.0
HC-1,3-BD	0.08000	0.07972	99.6	0.08427	105	0.08619	108	106
1,2,4-TCBZ	0.49896	0.491	98.4	0.501	100	0.579	116	108
HCCPD	0.80262	0.761	94.8	0.713	88.8	0.804	100	94.4
1,2,4,5-TCBZ	0.08526	0.08545	100	0.08919	105	0.09420	110	108
1,2,3,4-TCBZ	0.04900	0.04900	100	0.04392	89.6	0.04607	94.0	91.8
2-CL-NAPHTH	2.2218	2.33	105	2.2326	100.5	2.369	107	104
CL5-BZ	0.04371	0.04393	101	0.03522	80.6	0.04663	107	93.8
1,2-DCNAPHTH	0.4000	0.399	99.8	0.408	102	0.418	104	103
CL6-BZ	0.1015	0.102	100	0.09356	92.2	0.1146	113	103
ALPHA-BHC	0.2004	0.201	100	0.204	102	0.210	105	104
GAMMA-BHC	0.3661	0.367	100	0.3633	99.2	0.3773	103	101
1,2,3,4-TCNAPHT	0.4000	0.402	100	0.401	100	0.410	102	101
DMP	—	—	—	—	—	—	—	—
DEP	2.574	—	—	2.745	107	3.662	142	124
DNBP	10.416	11.351	109	8.649	83.0	8.345	80.1	81.6
BUBZP	4.864	4.906	101	3.505	72.1	3.539	72.8	72.4
BZEHP	3.663	—	—	—	—	—	—	—
DNOCP	4.257	—	—	—	—	—	—	—
F8-BIPHENYL**	2.000	1.991	99.6	2.319	116	2.379	119	117

* Analytes defined in Table 38.
**Spike used in all MM5 Trains.

Note: SK = Spike
%R = Percent recovery

The general requirements that have been placed on the program are the following: (a) protection of the personnel who will be responsible for the operation of the facility, (b) protection of the surrounding area, including members of the community and the environment and (c) protection of the facility and its equipment.

Operationally, the program is divided along a natural separation into normal and emergency operations. The former deals with the everyday operation of the facility and the routine safety protocols. The latter deals with the activities that will be brought into play under unusually hazardous circumstances; for example, response to a spill resulting from an incident on-site or during transport of the waste to the site.

As a first step in implementing the Safety Program, and before personnel arrived on-site, a Health and Safety Manual was prepared describing in detail the elements of the program and procedures to be followed. All personnel are required to be familiar with this document.

Although not a complete listing, the following summarizes some of the most important elements of the program which have been fully implemented.

An important part of any safety program is the monitoring of the health of individuals involved in the program. The medical program at the CRF includes a pre-employment examination designed to create a set of baseline parameters for future comparison, assess risk of individuals involved in specific operations at the CRF and determine the ability of personnel to utilize respiratory protection. All examinations will be repeated on an annual basis or more often when required. All personnel terminating employment at the CRF will be required to take an exit examination.

For those operations for which appropriate engineering controls cannot be implemented, personal protective clothing and equipment are required for hazardous operations. Equipment and clothing have been purchased, and a continuing training program is being conducted to assure that personnel can and will properly use it. An on-going monitoring program is in operation to assure that engineering controls are working properly and to document exposure levels of personnel to toxic chemicals. (An additional goal that fits into the overall mission of the CRF is the development of accurate and cost effective methods for monitoring the safety of commercial incinerators.) Basic equipment for this program is available with calibration and testing of the equipment continually updated.

A successful safety program requires a significant amount of training of personnel. All personnel at the CRF have been informed of: 1) Why a safety program is required; 2) The nature of and toxic effects of materials to be handled; 3) The need for protective measures such as special work practices, protective clothing and equipment; 4) Employee rights; and 5) The need for medical surveillance and confidentiality of medical information. CRF personnel have been trained in proper use of personnel protective equipment and clothing, maintenance of safety equipment (i.e. laboratory face hoods) and emergency response procedures.

All existing CRF operations and equipment are regularly inspected for safety. In addition, all proposed modifications in procedures and equipment are reviewed with safety in mind. The following list contains some of the more significant results of these activities to date:

1) Upgrading the personnel decontamination facility to better protect the facility's integrity and personnel working in uncontaminated areas.

2) Upgrading laboratory hoods for handling carcinogens.

3) Upgrading ventilation devices for equipment located in the Characterization and Thermal Decomposition Laboratories.

4) Modify rotary kiln seals to ensure efficient operation of the incinerator as well as minimize the chance of toxic materials being released into the incinerator room.

5) Design of feed system for leak-free operation and purging to avoid contamination of personnel and the facility with unprocessed waste.

6) Use of on-line areal monitoring equipment both in the facility and adjacent to the facility.

APPENDIX A

OUTLINE FOR SYSTEM HEAT TRANSFER ANALYSIS

APPENDIX
OUTLINE FOR SYSTEM HEAT TRANSFER ANALYSIS

A step-by-step heat transfer analysis may be conducted for correlating the experimentally-determined heat losses with the system design parameters and with operating conditions. The following steps might be taken:

A. Determine heat flux from combustion gases to the inner surface of the refractory insulation for each run, Q_L in Btu/hr, using the heat losses (of Table 32) in each section and the appropriate inside areas (from Table 33).

B. Determine radiation heat flux from the flame in each chamber to the inside refractory surface.

B.1 Determine theoretical maximum flame temperature of propane-air mixtures as a function of air-to-propane ratio. Take into account dissociation of molecular species (O_2, N_2, CO_2, H_2O, HCl) to free radicals.

B.2 For each run, use measured air-to-propane ratio in the kiln burner and in the afterburner burner to determine (from results of B.1) theoretical flame temperatures in each chamber.

B.3 Approximate the radiant heat flux by:

$$q_R = 0.173\ \epsilon \left[\left(\frac{T_f}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4\right]$$

where q_R = Radiant heat flux, Btu/ft^2, hr

T_f = Flame temperature, °R

T_w = Temperature at inside of refractory wall, °R

ϵ = Effective emissivity

As a first approximation, use T_f = Theoretical maximum flame temperature, and T_w = Measured combustion gas temperature. Both will be somewhat higher than actual, and the effects may be compensating. Also use(1)

$$\varepsilon = \frac{1}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1}$$

where ε_f = emissivity of flame ≅ 0.4

ε_w = emissivity of wall ≅ 0.8

B.4 Apply q_R to each section by multiplying by the appropriate inside area, to generate values of Q_R in Btu/hr. The kiln-to-afterburner transfer duct "sees" both the kiln burner flame and the afterburner burner flame, while the afterburner exhaust duct does not "see" the flame.

C. Determine convective heat flux from the combustion gases in each section to the inside surface of the refractory.

C.1 Determine k, the thermal conductivity of the combustion gases in each section, at the measured temperatures. Assume k varies linearly with temperature,⁽²⁾ and interpolate data for oxygen,⁽³⁾ nitrogen,⁽⁴⁾ and water,⁽⁴⁾ and extrapolate data for carbon dioxide⁽⁵,⁶⁾ and hydrogen chloride.⁽⁵⁾ Compute k of mixture using gas compositions.

C.2 Determine the heat capacity C_p for each constituent at the measured gas temperatures using $C_p = A+BT+CT^2$ (values of A,B, and C previously given). Compute C_p of the mixture using gas compositions.

C.3 The viscosity μ was previously determined (Table 27).

C.4 Calculate the Prandtl number, N_{Pr}

$$N_{Pr} = C_p \; \mu/k$$

C.5 The Reynolds number, N_{Re}, was previously determined (Table 27).

C.6 For each run, in each section of the system, calculate the inside convective heat transfer coefficient h_i (Btu/hr, ft², °F) from the Nusselt number, N_{Nu}

$$N_{Nu} = \frac{h_i D_i}{k} \quad ,$$

which in turn is calculated from

$$N_{Nu} = 0.023 \; N_{Re}^{\;0.80} N_{Pr}^{\;1/3}$$

C.7 Apply the appropriate inside surface area A_i for each section to the values of h_i to determine the convective heat flux Q_c (in Btu/hr) in terms of the inside wall temperature T_w:

$$Q_c = h_i A_i \ (T_c - T_w),$$

where T_c is the measured combustion gas temperature in each section (assume T_c for the transfer duct is the same as T_c for the kiln).

D. Determine the inside wall temperature T_w for each run by matching the total heat flux Q_L from (A) with the sum of Q_R (from B.4) and Q_c (from C.7). A second iteration using the new value for T_w in (B.3) might be desired.

E. Determine the heat flux from the outside shell of each section to the ambient air.

E.1 Summarize the average skin temperatures T_s for each section (from data in Table 19) for each run.

E.2 Summarize the average ambient air temperatures T_a for each run, using the dry bulb temperatures of Table 3 and/or the combustion air temperatures of Table 32.

E.3 Determine the outside temperature difference $\Delta T_o = T_s - T_a$, and the outside film temperature $T_f = \frac{1}{2} (T_s + T_a)$, for each section and for each run.

E.4 Calculate the outside heat transfer coefficient h_o (Btu/hr, ft^2, °F) for natural convection as follows:(7)

*For the afterburner cylinder and for the kiln cylinder

$$h_o = 0.5 \ {\frac{\Delta T_o}{12 D_o}}^{0.25}$$

*For vertical plates greater than 3 feet high, such as the end plates of the afterburner and of the kiln,

$$h_o = 0.27(\Delta T_o)^{0.25}$$

*For smaller vertical plates of height H feet such as those in the transfer duct and the exhaust duct,

$$h_o = 0.28(\Delta T_o/H)^{0.25}$$

*For horizontal plates facing upward,

$$h_o = 0.38(\Delta T_o)^{0.25}$$

*For horizontal plates facing downward,

$$h_o = 0.2(\Delta T_o)^{0.25}$$

E.5 Determine the outside heat transfer coefficient h_o for the rotating drum of the kiln using forced convection:(9)

$$N_{Nu}N_{Pr}^{-0.3} = 0.35 + 0.56\, N_{Re}^{0.52}$$

$$\text{and } N_{Nu} = \frac{h_o D_o}{k},$$

where the transport properties ρ, μ, k, and C_p are evaluated for air at the film temperature T_f, and where the velocity for the Reynolds number is the circumferential speed of the rotating drum. If h_o determined for forced convection is greater than for natural convection, it should be used.

E.6 Apply the appropriate outside surface area A_o for each section to determine the heat flux from the outside surface to the air, Q_o in Btu/hr, for each section and for each run:

$$Q_o = h_o A_o \Delta T_o$$

F. Extrapolate to Steady-State Conditions of Heat Transfer

F.1 Determine the rate of heat absorption (under non-steady-state conditions) by the refractory insulation and the steel shell as the difference between Q_L from (A) and Q_o from (E).

F2. For steady state conditions, calculate the equilibrium temperature difference between the inside wall and the outside wall as a function of the steady state heat flux Q_{ss}

$$(T_w - T_s)_{ss} = \frac{Q_{ss}}{A_M} \cdot \frac{X}{k} ,$$

where X is the insulation thickness

k is the thermal conductivity of the material

A_M is the mean area normal to the heat flow.

For the cylindrical sections of the afterburner and the kiln,

$$A_M = \frac{A_o - A_i}{\ln(A_o/A_i)}$$

For the flat plate sections of uniform wall thickness X, with length L and with inside edge lengths E:(8)

$$A_M = A_i + 0.54L\sum E + 1.2X^2$$

REFERENCES

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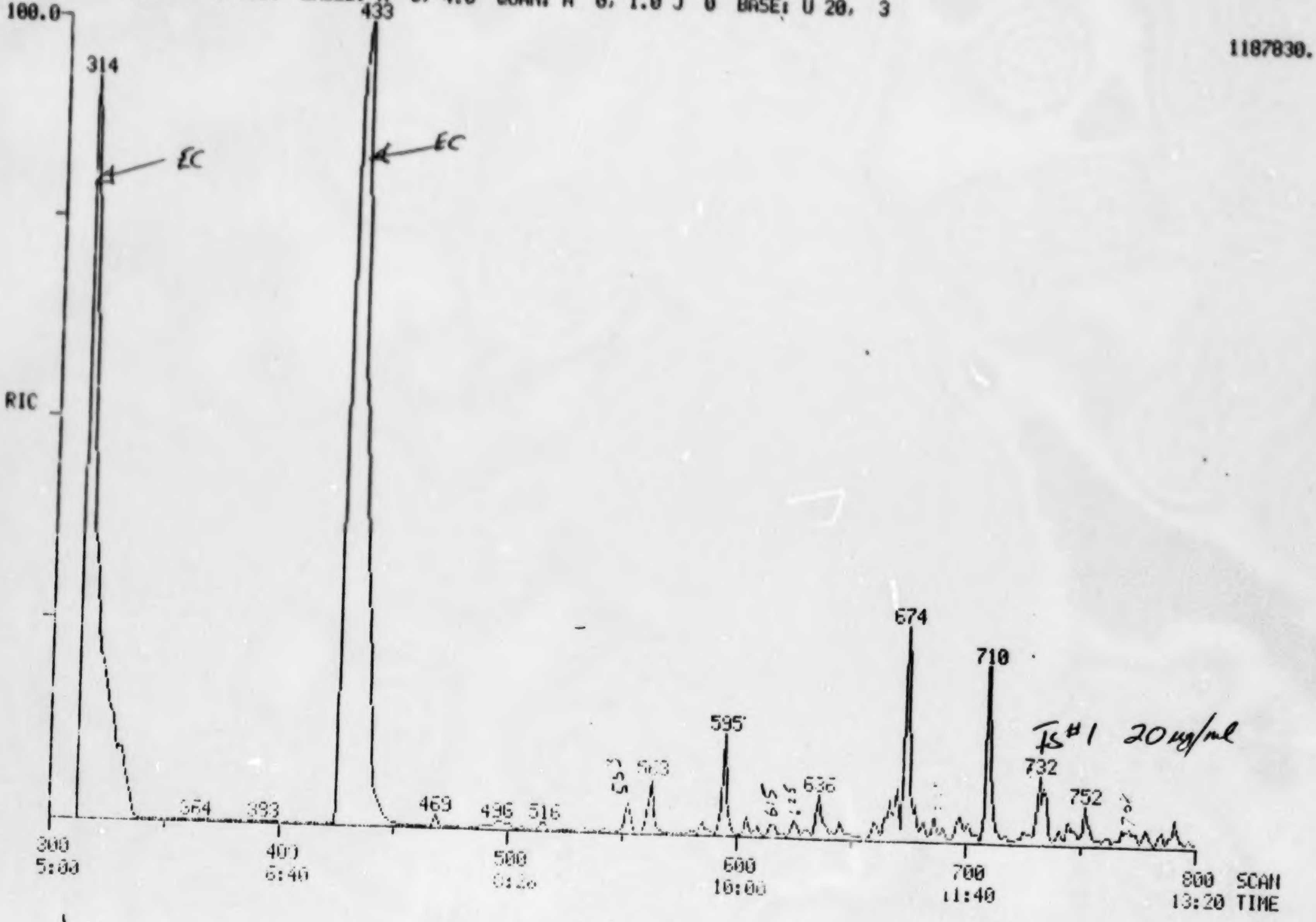
3. Weast, R.C. (ed.), Handbook of Chemistry and Physics, 58th edition, CRC Press, Cleveland, 1977, pp. F-74 to F-76.
4. Ibid., p. E-3.
5. Ibid., p. E-2.
6. Perry, J.H. (ed.), Chemical Engineer's Handbook, 3rd ed., 1950, p. 461.
7. Perry, J.H. (ed.), Chemical Engineer's Handbook, 3rd ed., 1950, p. 474.
8. Perry, J.H. (ed.), Chemical Engineer's Handbook, 3rd ed., 1950, p. 460.
9. McCabe, W.L., and J.C. Smith, Unit Operations of Chemical Engineering, McGraw-Hill, New York, 1956, p. 459.

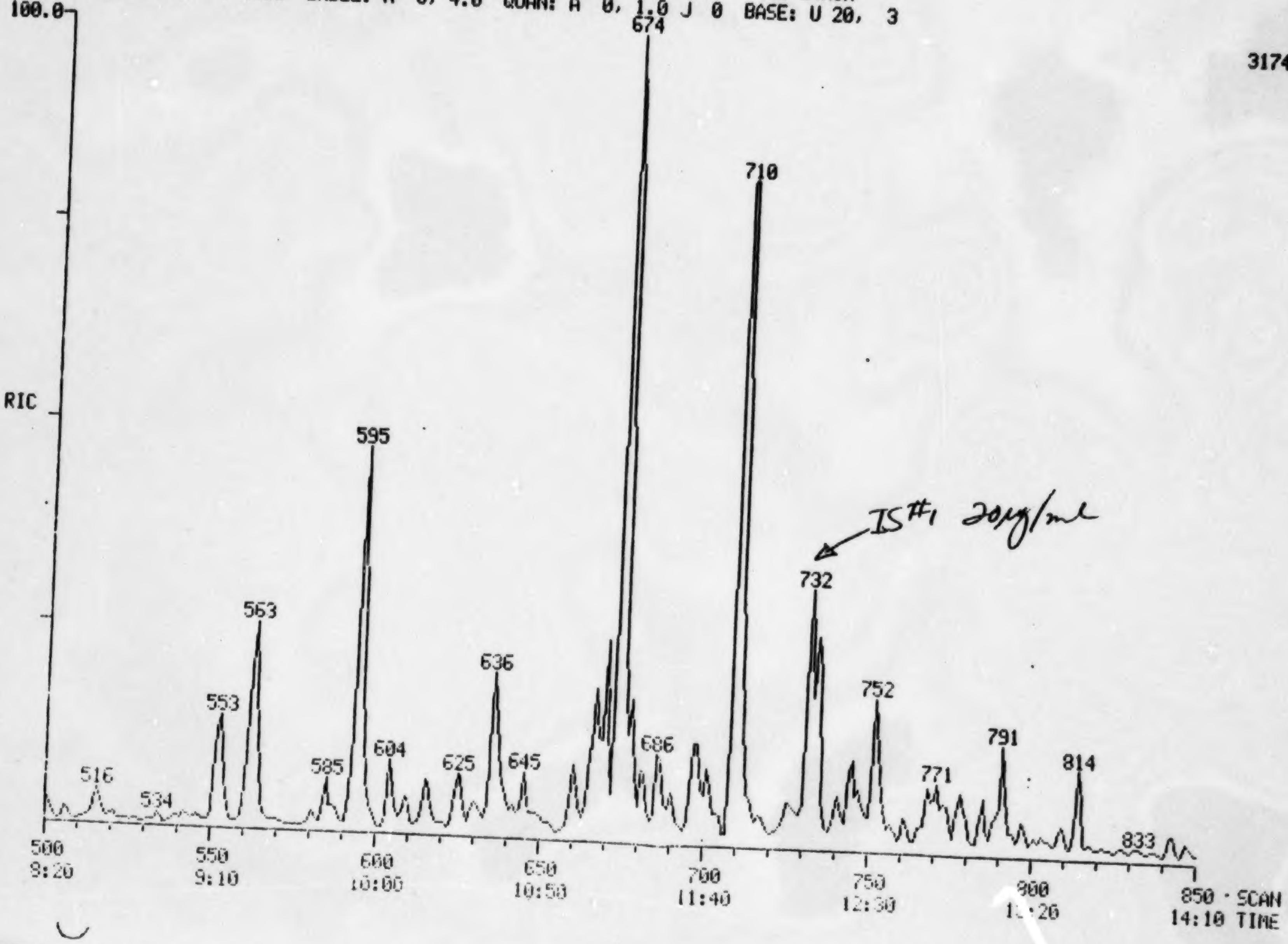
APPENDIX B

MASS SPECTRUM OF SAMPLE NO. M12081213

```
RIC
05/08/84 17:46:00                DATA: 1475 #1            SCANS  300 TO  800
                                 CALI: 1475 #5
SAMPLE: CRF EXTRACT M12081213 1UL OF 0.5ML STRAIGHT FINN 4000
CONDS.: SPB-5 30M*0.32MMID 1.0UMDF 30C/4.2MIN>280C@10C/MIN HOLD 24MIN
RANGE: G   1,3500  LABEL: N  0, 4.0  QUAN: A  0, 1.0 J  0  BASE: U 20,  3
```

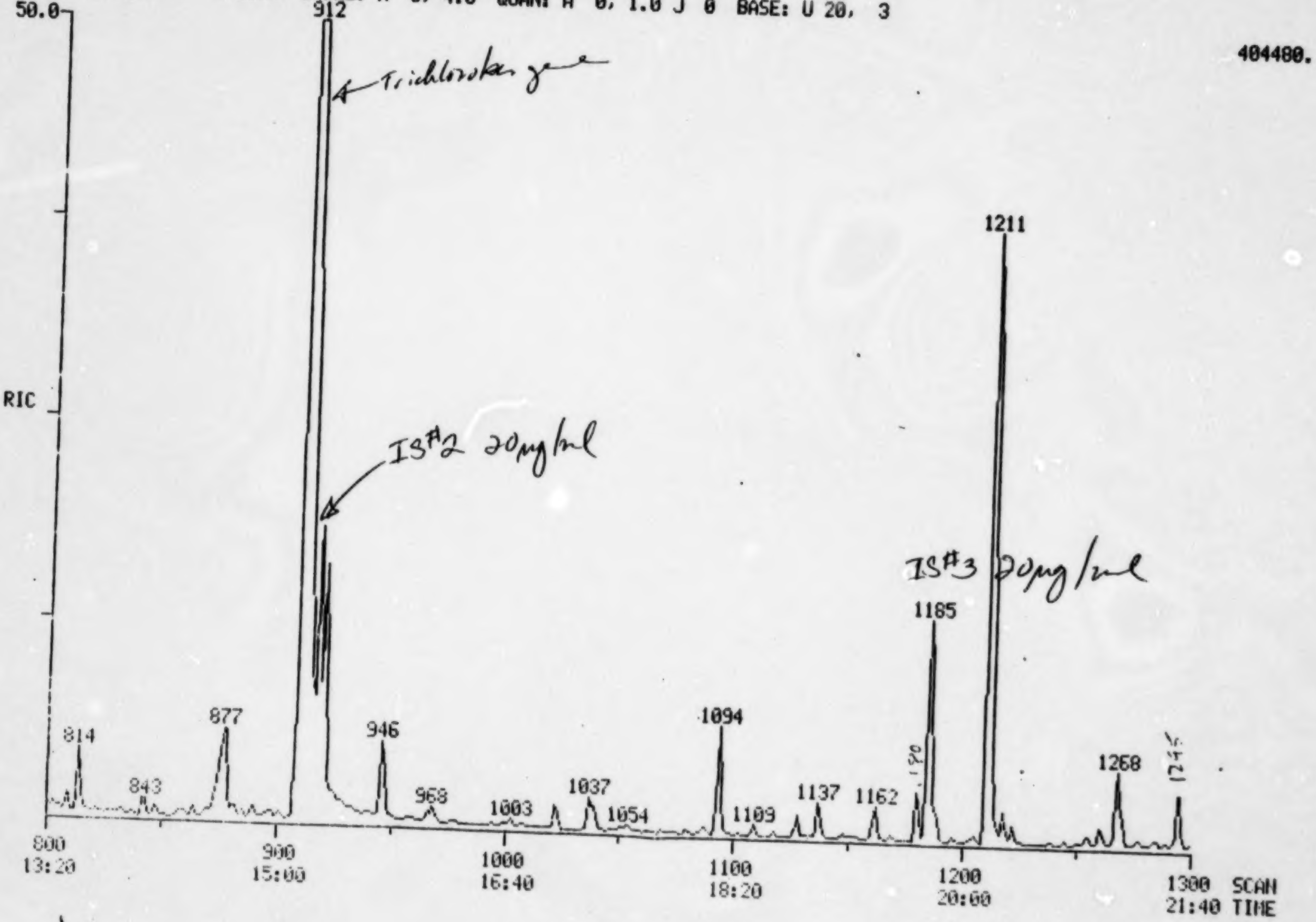


```
RIC
05/08/84 17:46:00                DATA: 1475 #1            SCANS  500 TO  850
                                 CALI: 1475 #5
SAMPLE: CRF EXTRACT M12081213 1UL OF 0.5ML STRAIGHT FINN 4000
CONDS.: SPB-5 30M*0.32MMID 1.0UMDF 30C/4.2MIN>280C@10C/MIN HOLD 24MIN
RANGE: G   1,3500  LABEL: N  0, 4.0  QUAN: A  0, 1.0 J  0  BASE: U 20,  3
```



IS#1 20µg/ml

RIC
05/08/84 17:46:00 DATA: 1475 #1 SCANS 800 TO 1300
CALI: 1475 #5
SAMPLE: CRF EXTRACT M12081213 1UL OF 0.5ML STRAIGHT FINN 4000
CONDS.: SPB-5 30M*0.32MMID 1.0UMDF 30C/4.2MIN>280C@10C/MIN HOLD 24MIN
RANGE: G 1,3500 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3

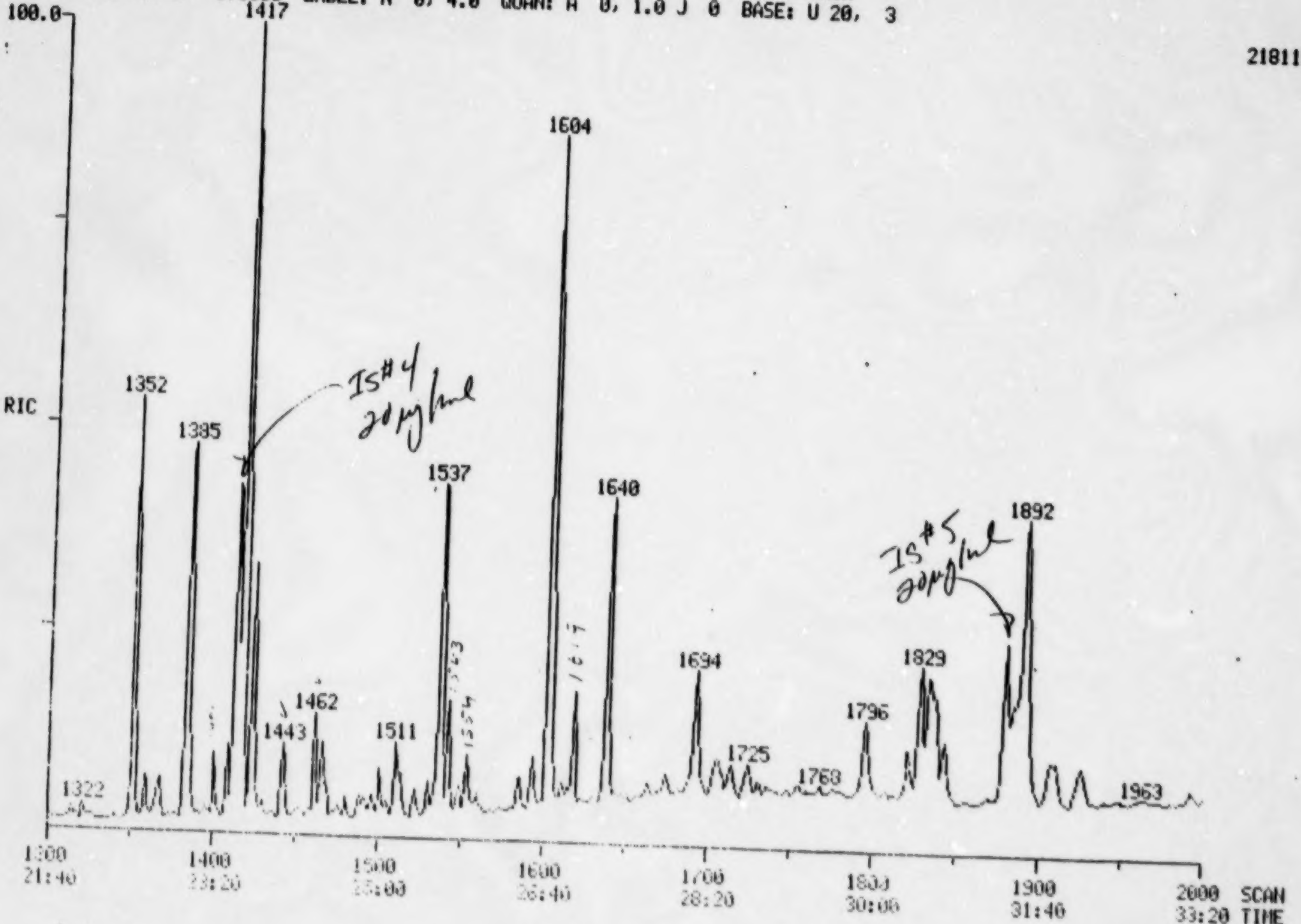


2-16

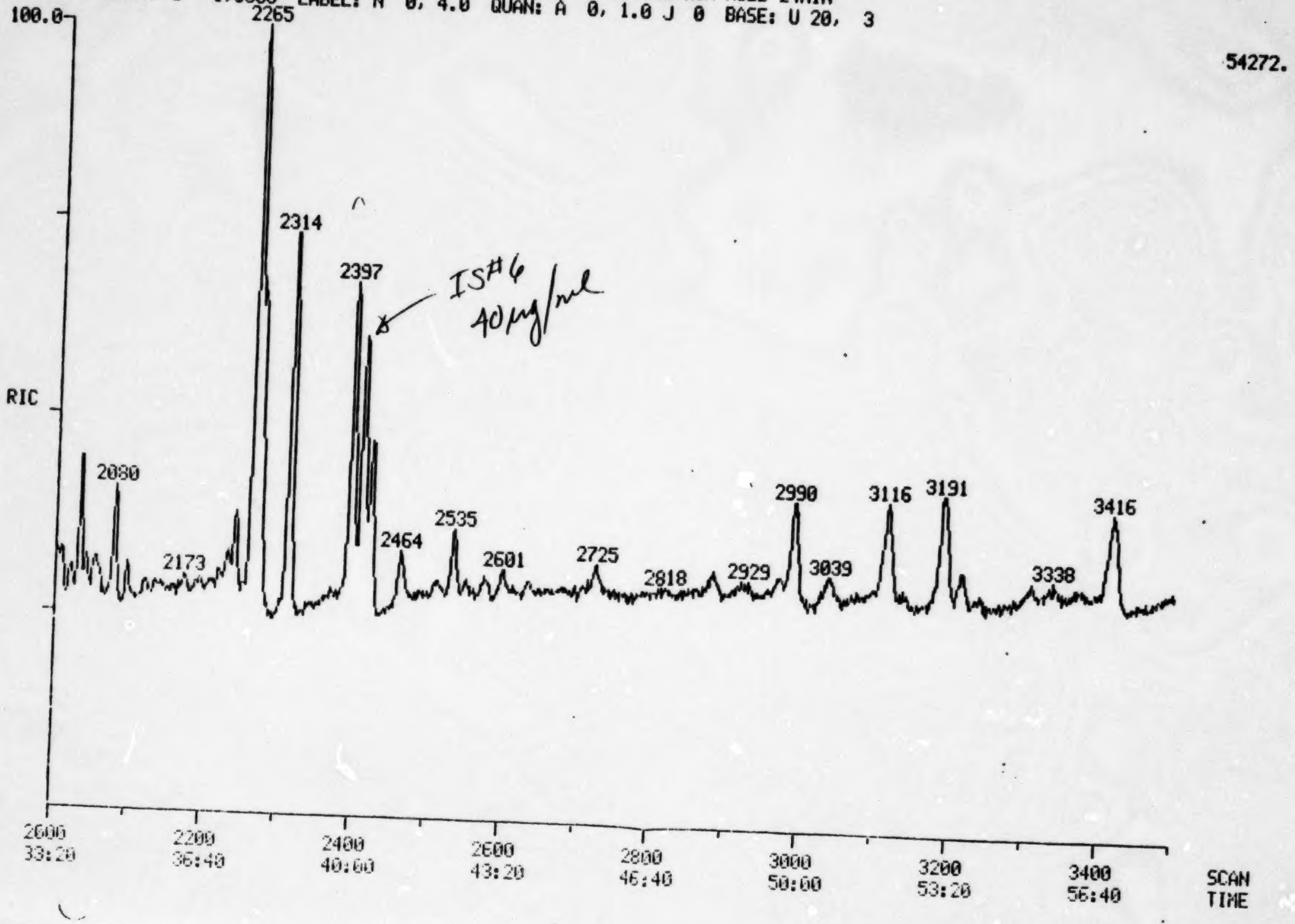
RIC
05/08/84 17:46:00 DATA: 1475 #1 SCANS 1300 TO 2000
CALI: 1475 #5
SAMPLE: CRF EXTRACT M12081213 1UL OF 0.5ML STRAIGHT FINN 4000
CONDS.: SPB-5 30M*0.32MMID 1.0UMDF 30C/4.2MIN>280C@10C/MIN HOLD 24MIN
RANGE: G 1,3500 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3

218112.

P-17



RIC
05/08/84 17:46:00   DATA: 1475 #1   SCANS 2000 TO 3500
                                 CALI: 1475 #5
SAMPLE: CRF EXTRACT M12081213 1UL OF 0.5ML STRAIGHT FINN 4000
CONDS.: SPB-5 30M*0.32MMID 1.0UMDF 30C/4.2MIN>280C@10C/MIN HOLD 24MIN
RANGE: G   1,3500 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3



IS#6
40µg/ml